Practical Electronics

The UK's premier electronics, computing and maker magazine

Circuit Surgery
Implementing digital sinc low-pass filters

The History of Electronics
Part two covers inventors born between 1804 and 1847

Precision Electronics
Choosing and using highly accurate op amps

Switching mains-powered devices on and off in sequence

Transmitting sound using a laser beam

Model Railway Points Controller

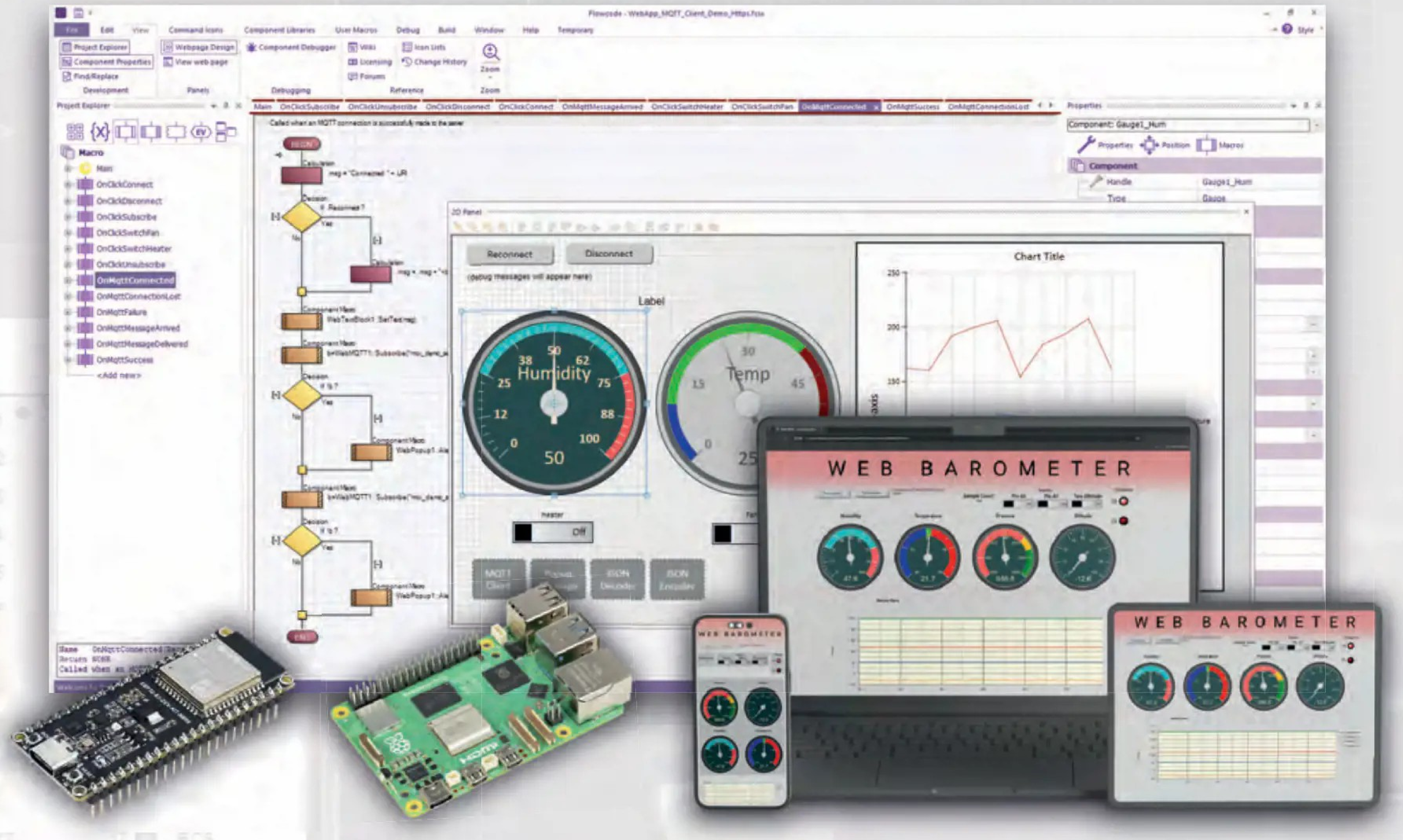
PLUS!

Techno Talk – could an AI help to keep you company?
Cool Beans – using NeoPixels for a colour matrix display
Net Work – wireless weather stations and nuclear power

Feb 2025 £5.99

www.electronpublishing.com | @practicalelec | practicalelectronics

FLOWCODE


Humidity
Temp
Chart Title
WEB BAROMETER
WEB BAROMETER

CREATE HIGHLY FUNCTIONAL ELECTRONIC SYSTEMS USING LOW COST HARDWARE, LIKE ESP32 AND RPI, TO CREATE FANTASTIC HUMAN MACHINE INTERFACES FOR YOUR PROJECTS AND MOBILE PHONES.

Flowcode hobby for ESP32 is FREE
Flowcode Pro with ESP32 pack £340 +VAT

10% off for PE readers using code: **WEB10**

FLOWCODE 10.1 WITH MORE THAN 20 MICROCONTROLLER TARGETS INCLUDING ARDUINO UNO, PIC18877, RPI2B, AND ESP32 IS NOW FREE FOR HOBBYISTS.

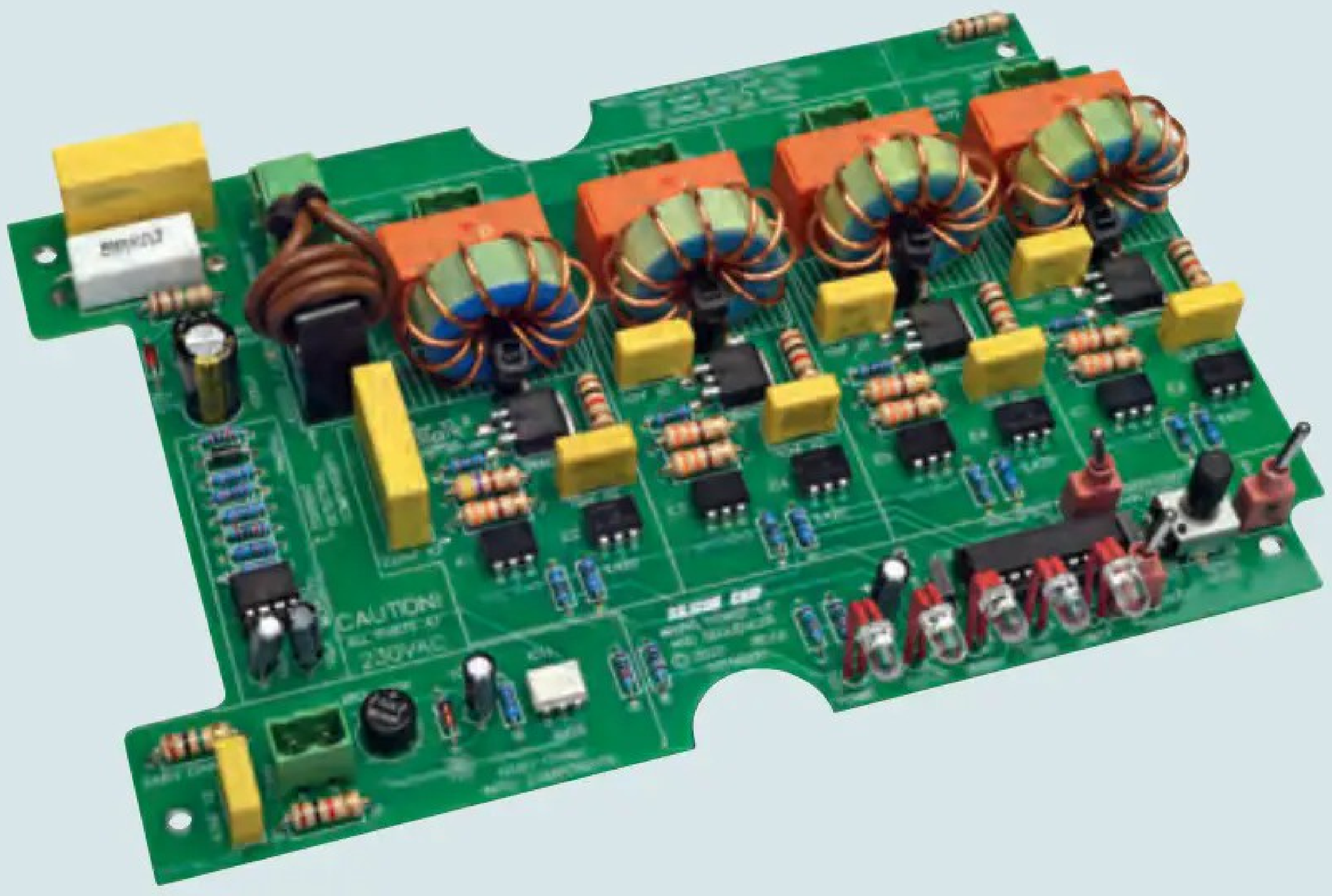
☎ +44 (0) 1422 252 380 — ✉ sales@matrixtsl.com

www.flowcode.co.uk

Practical Electronics

Volume 54. No. 2
February 2025
ISSN 2632 573X

Contents



Made in Australia & the UK.

Written in Britain, Australia, the USA and Ireland.

Read everywhere.

© Silicon Chip Publications Pty Ltd 2024-2025

Copyright in all drawings, photographs, articles, technical designs, software and intellectual property published in *Practical Electronics* is fully protected, and reproduction or imitation in whole or in part are expressly forbidden.

The March 2025 issue of *Practical Electronics* will be published on Wednesday, 5th of February 2025 (see p80).

Projects and Circuits

Laser Communicator by Phil Prosser 8
This fun project is ideal for learning electronics. It modulates a laser diode to transmit voice (or other audio) over several metres. The circuitry is quite simple and assembly is straightforward, so it is perfect as a teaching aid or introducing children to electronics.

Model Railway Points Controller by Les Kerr 37
Adding points to a model railway layout makes it more fun and realistic. This Controller lets you monitor and switch up to eight sets from a single box with easy wiring. We will also show how to make LED-based signals to go with each set of points.

Mains Power-Up Sequencer, part one by John Clarke 62
It solves many problems caused by powering up several devices simultaneously, like circuit breakers tripping and thumps from audio equipment. It can also power several appliances on or off when a 'master' appliance switches on or off.

Series, Features and Columns

Net Work by Alan Winstanley 4
I used a wireless weather station to banish indoor condensation; you can check the live weather data online. I also have an update on Britain's Small Modular Reactor program.

Circuit Surgery by Ian Bell 19
Implementing digital sinc filters and simulating them in LTspice.

The Fox Report by Barry Fox 24
Is Hi-Fi making a comeback? I also discuss the new EU digital tagging law.

Practically Speaking by Jake Rothman 26
Some unusual things happened during Jake's career working on audio electronics.

Techno Talk by Max The Magnificent 28
AI discovers the importance of flattery and it might be able to keep you company.

Max's Cool Beans by Max The Magnificent 30
Weird & Wonderful Arduino Projects, part two: power for our retro games console.

Precision Electronics, part two by Andrew Levido 48
This series about precision electronics design covers a range of topics and uses real examples and real components to demonstrate the concepts. This one picks up where the last left off and goes into much more detail about how to use op amps.

The History of Electronics, part two by Dr David Maddison 54
We wouldn't have computers, smartphones or AI without the work of thousands of people who created the foundations of modern electronics. This second part describes significant discoveries by people born between 1804 and 1847.

Using Electronic Modules – Adjustable USB Power Supply by Jim Rowe 73
This surprisingly inexpensive module converts 5V DC from a USB port into any DC voltage between 1V and 24V at up to 3W.

Regulars and Services

Editorial 2
AI is incredible but still in its infancy

Reader services – Editorial and Advertising Departments 2

Subscribe to Practical Electronics and save money 29

Practical Electronics back issue downloads 72

Practical Electronics PCB Service 76
PCBs for Practical Electronics projects

Classified ads and Advertiser index 79

Next month! – highlights of our next issue of Practical Electronics 80

Renewals paid by PayPal, Visa and Mastercard are now handled via our website:
www.electronpublishing.com

Practical Electronics

Volume 54. No. 2
February 2025
ISSN 2632 573X

Editorial

Editorial offices
Electron Publishing (Aust.)
Unit 1, 234 Harbord Road
Brookvale NSW 2100
Australia
Tel +61 2 9939 3295
Email pe@pemag.au
Web www.electronpublishing.com

Address mail to:
Electron Publishing (Australia)
PO Box 194, Matraville NSW 2036
Australia

Advertising enquiries
+61 2 9939 3295 pe@pemag.au

Editor	Nicholas Vinen
Publisher	Nicholas Vinen
Digital subscriptions	Stewart Kearn **Tel** 01202 880299
Online Editor	Alan Winstanley
Web Systems	Kris Thain
Production	Bao Smith
Technical staff	Tim Blythman, John Clarke

Print subscriptions
Practical Electronics Subscriptions
PO Box 6337
Bournemouth BH1 9EH
United Kingdom
Tel 01202 087631
Email pesubs@selectps.com

Technical enquiries

We regret that technical enquiries cannot be answered over the telephone. We are unable to offer any advice on the use, purchase, repair or modification of commercial equipment or the incorporation or modification of designs published in the magazine.

Questions about articles or projects should be sent to the editor by email: pe@pemag.au

Projects and circuits

All reasonable precautions are taken to ensure that the advice and data given to readers is reliable. We cannot, however, guarantee it and we cannot accept legal responsibility for it.

Some projects and circuits published in *Practical Electronics* employ voltages that can be lethal. Do not build, test, modify or fix any mains-powered equipment unless you fully understand the safety aspects involved and you use an RCD (GFCI) adaptor.

Component supplies

Silicon Chip Publications may offer kits or other parts for making our projects, but not in all cases. When kits are not available, readers will need to find and source parts themselves. We advise readers to check that all parts are still available before commencing any project in a back-dated issue.

Advertisements

Although the proprietors and staff of *Practical Electronics* take reasonable precautions to protect the interests of readers by ensuring as far as practicable that advertisements are bona fide, the magazine and its publishers cannot give any undertakings in respect of statements or claims made by advertisers, whether these advertisements are printed as part of the magazine, or in inserts. The Publishers regret that under no circumstances will the magazine accept liability for non-receipt of goods ordered, or for late delivery, or for faults in manufacture.

Transmitters/bugs/telephone equipment

We advise readers that certain items of radio transmitting and telephone equipment which may be advertised in our pages cannot be legally used in the UK. Readers should check the law before buying any transmitting or telephone equipment, as a fine, confiscation of equipment and/or imprisonment can result from illegal use or ownership. The laws vary from country to country; readers should check local laws.

AI is incredible but still in its infancy

Over the last few months, including in this issue, we have had quite a few columns that mention how widespread artificial intelligence (AI) has become.

In some cases, like the dehumidifier that Alan Winstanley describes in this month's Net Work column, the use of the term AI is quite dubious. I suspect that the word "AI" is often simply slapped onto a product to make it seem more trendy.

It was OpenAI who really brought on the modern AI era with their introduction of ChatGPT (ironically based on technology developed by Google, who are now working very hard to compete with OpenAI). In many ways, ChatGPT remains the most spectacular implementation of AI, especially in its latest 4o guise.

I've noticed in the last month or so that ChatGPT has gotten a lot better at running web searches to find information that's outside its immediate knowledge.

Even more impressively, you can converse with it like you would another person. It doesn't just generate dry text – it can talk to you with nuances in its 'voice', even joining in if you start singing!

While you can argue about how far off artificial general intelligence (AGI) is, and indeed whether it can ever be achieved, I think it's already very close to passing the Turing Test. It may even already be capable of doing so.

The main thing that gives AI away is that I can recognise its writing style. Still, that's no different from a real person, I suppose.

What's really holding it back is the fact that it's difficult to trust. For example, let's say you're working on a book. You feed what you've written into ChatGPT and ask it to tidy it up and improve it for you. It's very capable of doing that sort of job. But could you publish the result without checking it very carefully?

I think you would have to read through and check everything it produced, lest it introduce nonsense in the middle – something it is still prone to doing. Until that can be solved, it will have to be relegated to the role of advisor, something that it is actually very good at.

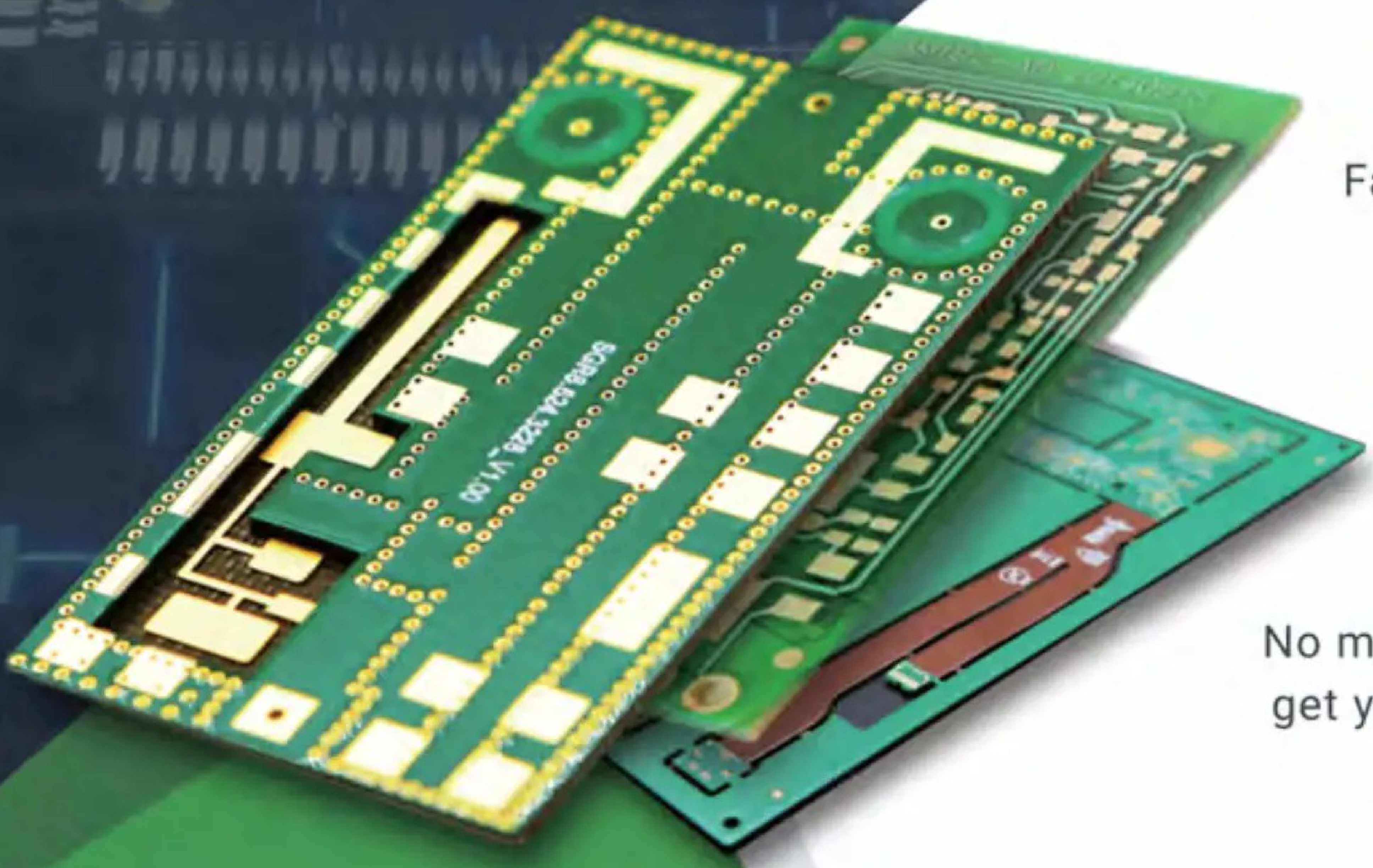
Nicholas Vinen, Electron Publishing (Australia)*
Publisher & Editor,
Practical Electronics Magazine

* a division of Silicon Chip Publications Pty Ltd.

PCBWay

EMPOWERING AI INNOVATION, ONE PCB AT A TIME

In the rapidly advancing world of AI, precision and reliability are essential. PCBWay provides high-quality PCB prototyping, assembly, CNC machining, and 3D printing services to bring your AI-driven projects to life. From robotics to smart devices, we offer a complete solution to power your next AI breakthrough.



Precision PCBs

Perfect for the complex designs that drive AI hardware.

Rapid Prototyping

Fast turnaround times as 24 hours to keep your innovations on schedule.

Global Reach

No matter where your lab or workshop is, we'll get your boards to you quickly and affordably.

End-to-End Support

We're more than manufacturers; we sponsor and collaborate with AI developers, startups, and makerspaces worldwide.

Why Choose Us?

With PCBWay as your partner, you can focus on pushing the boundaries of AI, while we ensure your hardware is up to the challenge.

Start building the future of AI today!

Visit PCBWay.com to discover how our PCBs can power your next AI innovation.

service@pcbway.com
www.pcbway.com

Net Work

Alan Winstanley

In this column, I explain how I used a wireless weather station to banish indoor condensation. You can check the resulting live weather data online. I also have an update on Britain's Small Modular Reactor program and electricity generation in general.

As I pen this month's column, we've had a taste of winter, with early snowstorms battering parts of the British Isles. Unlike many better-prepared countries, Britain almost grinds to a halt when the first snowflakes hit the ground. We are unaccustomed to wintry weather extremes that invariably catch us on the hop.

Apart from amateur weather watchers, others interested in the weather include horticulturists and growers, small boat owners, fishpond keepers and owners of solar panels (or home wind turbines, for that matter).

I introduced my new internet weather station in the July 2023 and January 2024 issues. It is an Ecowitt HP2551 WiFi-enabled system with a crystal-clear 7-inch (178mm) TFT display that logs various meteorological metrics on its colourful screen. It generates plenty of data that helps owners to recognise trends and anticipate weather conditions.

Additional sensors sold by Ecowitt can measure soil moisture, soil temperature and pond or pool water temperature. Pricier add-ons will monitor PM2.5 air quality (particulate matter density) and lightning strikes, although the data captured is only available on an app. Alarms can be set to warn of high winds or rainfall, although I find the console's on-board piezo buzzer is quite timid.

The weather station's 7-in-1 outdoor array (WS69) measures wind speed, gusts and direction, rainfall, humidity, temperature, UV index and solar radiation. It must be installed pointing to true north. European models use the reliable and less-crowded 868MHz frequency band to transmit data wirelessly.

Data can be stored on the console's microSD card for later use (eg, in Excel), but it can also upload to Ecowitt's cloud server and other popular weather websites. This month I'm sharing an exclusive link where readers can check my data online for themselves (see later).

Wed, 20 Apr 2019
11:24:09
36.7
2.0
35.7
60%
0.2 mm
1007.4
13.5
85%
Temperature, Humidity Pressure Sensor

The author used an Ecowitt HP2551 weather station like this one to check indoor humidity levels using multiple wireless sensors.

A single WH32 sensor is included that reads indoor temperature, humidity and atmospheric pressure, and you can add up to eight wireless sensors as your enthusiasm grows. In my case, this would prove very handy as I'm trying to tackle a condensation problem this wintertime, possibly caused by insufficient ventilation or insulation in the home.

AI with everything

Since indoor condensation is caused by warm, moist air hitting cold surfaces, I set up several Ecowitt WN31 temperature/humidity sensors around the house. I hoped to keep track of ambient humidity levels indoors, and I could also check the performance of a domestic dehumidifier bought especially for the winter season.

The British brand Ebac manufactures dehumidifiers designed especially for the British climate. Some models use an advanced and unique "Smart control AI" sensor instead of a basic humidistat that only measures relative humidity (RH). "Smart" here does not imply internet connectivity.

Ebac says its 'smart' approach is superior for British weather, as there's never an optimum RH figure anyway, because RH changes when the weather changes.

I chose the Ebac 3650e 18L 'smart' model (it extracts up to 18 litres per day), bought online direct from the makers at https://ebac.com/dehumidifiers/range

Online buying tip: hold back until special discount offers appear; direct

14.5 °C
64 % RH
CH 2
Temperature,Humidity Sensor

The Ecowitt WN31 indoor sensor has an LCD screen and monitors the local temperature and humidity.

VARTA
ULTRA LITHIUM
VARTA
ULTRA

A set of DIP switches at the rear of the WN31 indoor sensor select one of eight possible channels.

sales also attract an extended four-year warranty.

Moist air tends to rise (it's less dense than dry air), so I permanently plugged in the dehumidifier upstairs. Keeping internal doors ajar improves air circulation. The appliance then becomes the coldest spot in the house, where humid air is forced to condense before being collected in a tub, emptied daily. Alternatively, water can drain externally through a small pipe.

Using the Ecowitt weather station this way was an interesting exercise. Initially, I was astonished to see some three litres of water extracted every day before it settled down over the course of a few weeks. Continuously operating the Ebac costs about 45p a day, as shown by my Ketotek power meter (see *Net Work*, January 2024).

This UK-made Ebac dehumidifier has a unique 'Smart AI' humidity sensor.

Indoor humidity has fallen to 45-50% or so regardless of the weather. Best of all, the condensation problem has disappeared completely.

After 18 months of operation, I'm also pleased to say that the Ecowitt weather station still performs flawlessly. I've had no problems at all with sensor communications, even though the outdoor array is 30m or more away, and the console is located well inside the house with quite a few brick walls intervening.

Net Work's weather station

I'm now pleased to offer readers an opportunity to view some of my own live data on Ecowitt's servers, by visiting the special link at https://www.ecowitt.net/home/share?authorize=1HJ565

There's also a QR code you can snap with your smartphone. The URL is valid for up to one year and may change over time.

Graph lines can be toggled to hide or reveal parameters (eg, click the small Solar and UVI icons to show or hide the corresponding lines). The date range is selectable from a drop-down box.

It has been interesting to compare indoor humidity against outdoor weather. I was intrigued to see how the Ebac operated pretty much continuously during periods of heavy rain, until indoor humidity fell and it settled down again. The 'Smart AI' sensor is obviously working well.

If you don't want a fully fledged LCD weather display console, a simple low-cost 'gateway' is available that works with a smartphone app instead. The Ecowitt GW1200 would be a good place to start; a wide range of Ecowitt products is sold online.

One UK website that's worth checking is https://weatherspares.co.uk and Amazon also has a selection of Ecowitt products as well as dehumidifiers. AliExpress also lists many Ecowitt products, noting that prices exclude VAT.

Other popular dehumidifier brands include Meaco, De'Longhi and Pro Breeze, which are sold by the usual outlets. Many can also be used for drying laundry indoors. Incidentally, 'dessicant' types are the best choice for low-temperature locations such as garages, outbuildings or, say, caravans that are laid up over winter.

If you decide to pipe the dehumidifier's water outlet outside, remember to insulate the pipework so it cannot freeze up.

This QR code will display the author's weather station data in your browser.

Next, I'll try uploading data direct to the UK Meteorological Office Weather Observation Website (Met. Office WOW) at https://wow.metoffice.gov.uk – but that's a project for the winter holidays!

A gloomy outlook

There are a few German-language words that have no English equivalent; *schadenfreude* (relishing someone else's downfall) is an obvious one, but another word that recently joined our lexicon is *dunkelflaute*.

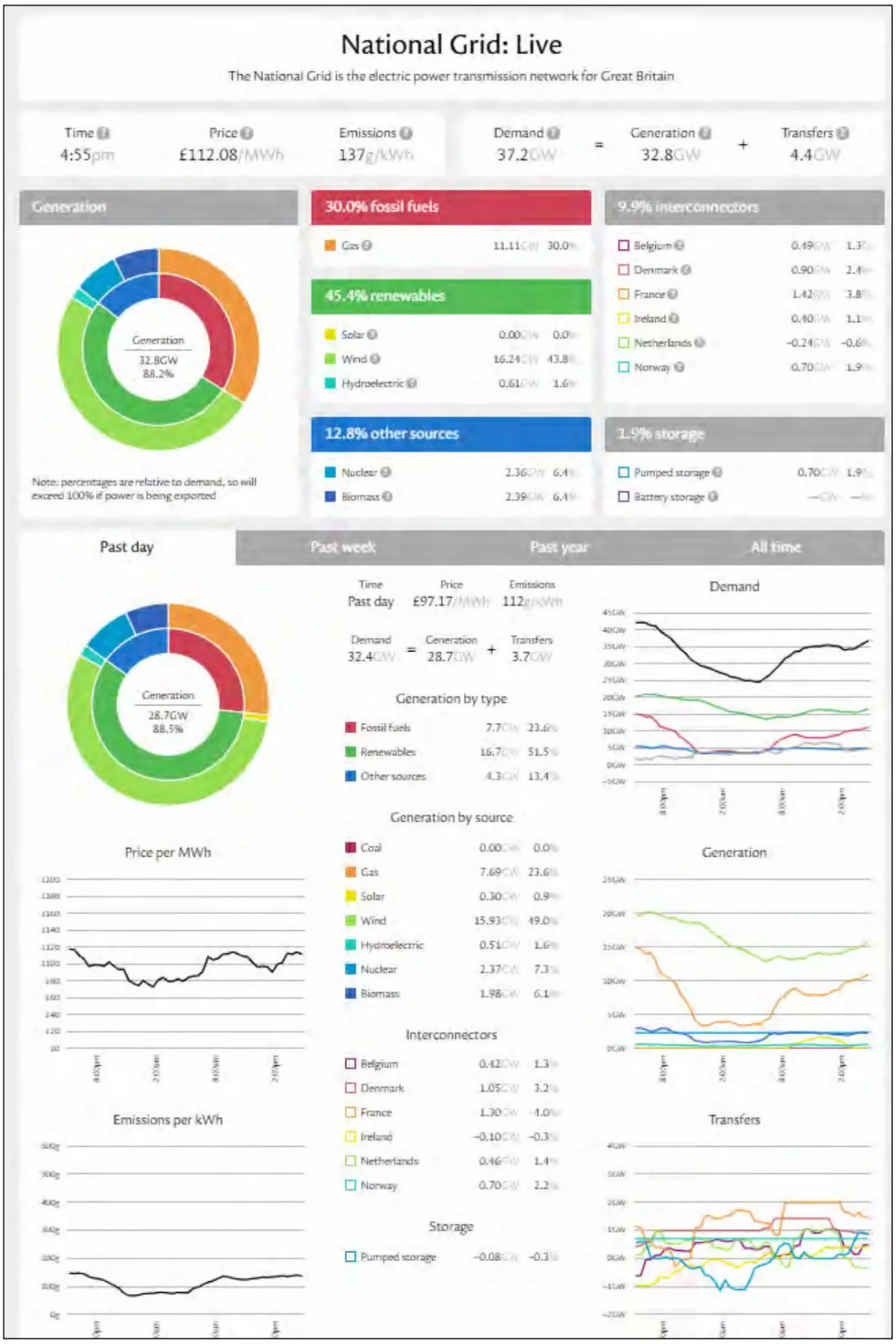
Britain's anti-cyclonic weather in early November saw a period of some 10 days or more with absolutely no sun, little wind and low cloud – a perfect *dunkelflaute*, or a gloomy lull in the depressing weather.

No amount of renewable solar or wind energy generation will be of much use during a dunkelflaute. November's miserable weather brought into sharp focus the UK's ongoing march towards 'Net Zero', as the country strives to move away from fossil fuels towards becoming self-sufficient in 'green' energy instead.

At such times, to keep the lights on we rely on storage battery farms, nuclear, biomass and fossil fuels, overseas interconnects and some hydroelectricity to top it up. The highly informative website at https://grid.iamkate.com designed by Kate Morley shows admirably the status of the National Grid as it edges perilously close to 100% during peak periods. See the example screen grab overleaf.

Data provided from the last ten years is insightful, as it also shows how energy costs of £35 per MWh in 2020 increased five-fold in 2022. International Energy Agency (IEA) statistics show that the UK now has easily the most expensive industrial energy costs anywhere in the Western world, 4.5 times higher than Norway's, for example.

At one time, the UK had an ambition to become entirely self-sufficient


National Grid: Live

The National Grid is the electric power transmission network for Great Britain

Time	Price	Emissions	Demand		Generation		Transfers
4:55pm	£112.08/MWh	137g/kWh	37.2GW	=	32.8GW	+	4.4GW

Generation: 32.8GW 88.2%

Note: percentages are relative to demand, so will exceed 100% if power is being exported

30.0% fossil fuels		
Gas	11.11GW	30.0%

45.4% renewables		
Solar	0.00GW	0.0%
Wind	16.24GW	43.8%
Hydroelectric	0.61GW	1.6%

12.8% other sources		
Nuclear	2.36GW	6.4%
Biomass	2.39GW	6.4%

9.9% interconnectors		
Belgium	0.49GW	1.3%
Denmark	0.90GW	2.4%
France	1.42GW	3.8%
Ireland	0.40GW	1.1%
Netherlands	-0.24GW	-0.6%
Norway	0.70GW	1.9%

1.9% storage		
Pumped storage	0.70GW	1.9%
Battery storage	—GW	—%

Time	Price	Emissions
Past day	£97.17/MWh	112g/kWh

Demand		Generation		Transfers
32.4GW	=	28.7GW	+	3.7GW

Generation: 28.7GW 88.5%

Generation by type		
Fossil fuels	7.7GW	23.6%
Renewables	16.7GW	51.5%
Other sources	4.3GW	13.4%

Generation by source		
Coal	0.00GW	0.0%
Gas	7.69GW	23.6%
Solar	0.30GW	0.9%
Wind	15.93GW	49.0%
Hydroelectric	0.51GW	1.6%
Nuclear	2.37GW	7.3%
Biomass	1.98GW	6.1%

Interconnectors		
Belgium	0.42GW	1.3%
Denmark	1.05GW	3.2%
France	1.30GW	4.0%
Ireland	-0.10GW	-0.3%
Netherlands	0.46GW	1.4%
Norway	0.70GW	2.2%

Storage		
Pumped storage	-0.08GW	-0.3%

Live National Grid electricity power data compiled by the IamKate website. Roll over the charts and graphs for more details.

in generating electricity from nuclear power. That was half a century ago, in 1975. I wrote about the UK's chequered history of nuclear power in *Net Work*, November 2022, which included details of the 1957 Windscale nuclear disaster.

Delayed reaction

Sixty years ago, Britain's forward-looking Government placed its bets on the wrong horse, backing the development of its own Advanced Gas-cooled Reactors (AGRs) to replace first-generation Magnox reactors, while the rest of the world was opting for Pressurised Water Reactors (PWRs) instead.

Fourteen AGRs were built after 1963, all of them used exclusively in the UK. Buoyed by the arrival of North Sea 'natural gas', the famous 1990 Creature Comforts TV adverts (shown in full on YouTube at **https://youtu.be/fBJ6pixLHtc**) implored us to use as much of this bounteous energy as we could!

After a two-year long public enquiry into the nuclear power sector, it wasn't until 1988 that construction started on Sizewell B, our first PWR, which finally went online in 1995. Sizewell C and Hinkley Point C are currently being constructed by France's EDF, and promise to generate electricity for the next 60 years.

Our first new nuclear power station in decades is long behind schedule, partly because Britain has had to relearn forgotten nuclear power construction skills all over again, says EDF.

The immense pressure on Britain's energy infrastructure has been well documented, and the rush to meet 'Net Zero' carbon emissions has created a perfect political storm. The last coal-fired power station has closed and some gas power stations have been bulldozed. Meanwhile, 'solar farms' are springing up that carpet agricultural land with Chinese-made solar panels.

Many 'green' ambitions are being pinned on wind power, such as the world's largest offshore wind farms being built at Dogger Bank and Hornsea, off the UK's east coast.

A network of undersea power and data cables now criss-crosses the world's oceans. Recently, a Chinese bulk carrier, the Yi Peng 3, was accused of dragging its anchor 100 miles to deliberately cut two cables in the Baltic Sea. Fortunately, the damage was swiftly repaired, and the ship is now being shadowed by NATO vessels. However, it's not thought that China was behind the episode.

In today's uncertain times, such resources are undoubtedly vulnerable to foreign interference. Thus, in 2023, the Royal Navy Fleet Auxiliary launched RFA Proteus, a converted oil-rig service vessel equipped with a helipad and remotely operated submersibles. It is dedicated to safeguarding undersea infrastructure such as energy supplies and data cables. A second vessel is scheduled to be built.

Meeting demands

In January 2022, I first described the prospect of the country adopting Small Modular Reactors (SMRs) to fill Britain's energy gap. For financial reasons, Japan's Hitachi and Toshiba had previously pulled out of building nuclear power plants in Britain, adding to Britain's power generation shortfall.

Hitachi's former sites in Wales have since been purchased by Great British Nuclear (GBN) as part of its future growth plans.

SMRs are nuclear power plants that can be assembled on-site using major prebuilt elements that can be transported by road. In 2022, SMRs were still a decade away, and a government 'competition' was held to produce a short-list of contractors that the UK would support in developing them. There was much flag-waving from

The new Royal Fleet Auxiliary Proteus is a vessel designed for undersea surveillance and warfare. Source: YouTube (Navy Lookout).

Rolls-Royce, but foreign rivals were eager to offer SMRs too.

France's EDF withdrew early from the race, followed by American company NuScale. The 'competition' finalists have now been announced as Rolls-Royce, GE-Hitachi, Holtec and Westinghouse.

Holtec Britain is already heavily involved with Britain's nuclear construction program and chose Doncaster in South Yorkshire as the site for a new SMR factory. Some 70% of components are to be UK-sourced. The world-famous Sheffield Forgemasters steelworks, now owned by the Ministry of Defence, is just up the road and produces highly specialised castings for the nuclear sector.

Holtec fast-tracked the regulatory approvals needed for its US-designed SMRs and, once approved, construction could start as early as 2026, the firm says, with 'shovel-to-startup life cycle' estimated as three years. Rolls-Royce is also known to be scouting locations to build several factories. GBN says that they will make the final decision on which technologies to select in the spring of 2025.

Until SMRs eventually come on stream and energy supplies loosen up, UK consumers are going to be encouraged (or bribed) to cut energy consumption at peak periods. Previous trials of the so-called 'Demand Flexibility Service' (DFS) over winter 2022/23 were deemed a success (even winning industry awards), and the scheme is again being offered this winter.

In a nutshell, DFS offers consumers with smart meters a rebate to encourage them to use power-hungry appliances such as washing machines during off-peak periods. This will shift demand on the electricity supply during so-called 'DFS events', when the supply operators struggle to match electricity demand with supply.

It's probably only a matter of time before 'Event' messages pop up on smart meter displays or via SMS, so consumer behaviour may well be manipulated that way too.

Hidden deeply in some small-print from the electricity system operators is a caveat, though:

Using electrical goods overnight can create an increased risk of an incident. We advise all consumers to follow the guidance offered by organisations such as the [campaigning charity] *Electrical Safety First* [**https://www.electricalsafetyfirst.org.uk/guidance/safety-around-the-home**] *and where possible to avoid using their electrical appliances overnight.*

In the meantime, let's hope that the country doesn't suffer from any more *dunkelflaute* and enjoys more *sonnenschein* instead!

As always, you can drop me a line at **alan@epemag.net** PE

An artist's impression of Holtec's proposed SMR-300 nuclear reactor site.

By Phil Prosser & Zak Wallingford

Build your own Laser Communicator

This project is fun and ideal for people learning electronics, especially kids. It introduces some basic skills, such as soldering, and demonstrates what can be achieved with simple circuits. It is perfect for building with young family members or as a teaching aid for students.

The Laser Communicator is for play; it is not a 'practical' device, although you might find uses for it beyond fun and learning, in which case, all power to you! As we all know, everything is better with a laser on it – even sharks!

So, what is the Laser Communicator? It allows you to transmit voice or music over a laser beam. That might be across the room, down the corridor or even further! The link is far from hifi and requires you to adjust things to make it work, but it isn't too hard to set up.

During testing and trials, my 10-year-old grandson, Zak, was able to talk over this down our corridor over a distance of about 15 metres. It would be fair to say that keeping things aligned over this distance was a challenge, as the deflection of our floorboards as we walked on them caused the laser to wobble around a lot at the receiver.

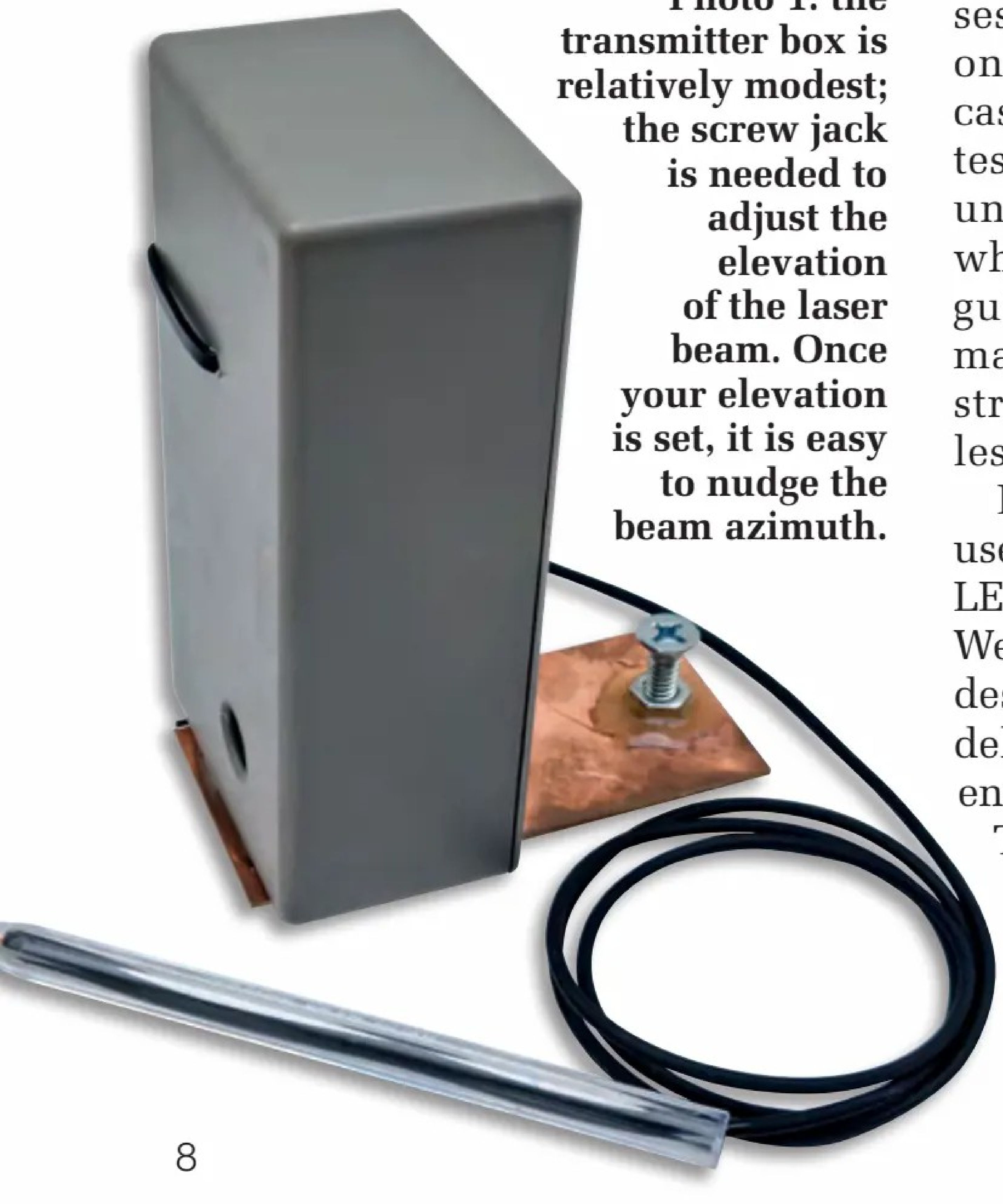


Photo 1: the transmitter box is relatively modest; the screw jack is needed to adjust the elevation of the laser beam. Once your elevation is set, it is easy to nudge the beam azimuth.

We have kept the layout very spread out and used beginner-friendly pads to keep construction straightforward. The hardest part of this project is cutting and drilling the enclosure. We have made the transmitter board so you can use it 'bare', but we think the boxed version is better if you can deal with making it.

Zak enjoyed drilling the mounting holes but left the larger speaker hole to my more experienced hands.

When building this with Zak, we split the PCB construction into two sessions of about an hour each, plus one for drilling and preparing the cases and another for assembly and testing. I made a point of building a unit alongside Zak to demonstrate what he needed to do, and with that guidance, he could undertake the majority of tasks alone. Older constructors may go faster and require less assistance.

Let's start with a caution. This project uses a laser (we could have used an IR LED, but that is nowhere near as fun). We have used a 1mW laser diode and designed the driver so that it cannot deliver more power than that, which ensures this remains a Class 2 laser. This is the same power level as your average laser pointer.

The Class 2 laser we are using will cause a "blink reflex", and people will normally look away. This Class 2 laser "Would not harm an eye unless a person deliberately stared into the beam. Laser protective eye wear is normally not necessary. A Class 2 laser is not a skin or materials burn hazard."

As a further caution, we have designed this circuit to operate the laser diode at 60% of its standard operating current. This results in the average laser output power being much lower than 1mW, giving us headroom to apply amplitude modulation to the laser output for transmitting the audio signal.

Laser beams have very low divergence, and even a 1mW laser can cause visual interference at well over 100m, so never point this toward people or vehicles. If you build this with a youngster, ensure that they fully understand that this is never to be pointed at a person, and supervise them while using it.

How does it work?

Many things in our day-to-day lives use wirelessly transmitted signals. TVs, radios and mobile phones all use the RF transmission of electrical signals. These systems use radio-frequency signals to transmit the data, with antennas at each end (transmitter and receiver).

In this project, we transmit the audio information optically using light (the laser) as the carrier. The actual audio is impressed on the light as an amplitude modulation, which means we are changing the intensity of the laser to carry the audio information we want to send.

One way to think about it is that it's a 430THz (terahertz) radio system, although electromagnetic radiation at that frequency certainly behaves a little differently compared to 430MHz or 5GHz!

We can amplitude-modulate a laser by changing the current through it, which is a simple way of implementing AM (that's basically how it's done for RF). At the receiver end, we need to sense the laser light and somehow turn the amplitude modulation into an electrical signal we can deliver to a speaker (ie, demodulate it).

Our approach is to use a photodiode and ignore the DC part of the intensity received by passing it through a series capacitor. The remaining AC part of the intensity is fed to the amplifier.

Both the transmitter and receiver are about as simple as we can make them, as this is a learning project. Much more complex approaches are used in a real-world laser communications system, but the spirit of this project is learning and some play.

The Laser Communicator comes in two parts: a transmitter and a receiver. Each fits in a standard Jiffy box: UB3 (130 × 67mm) for the transmitter and UB2 (197 × 112mm) for the receiver. The transmitter block diagram is shown in Fig.1, while the receiver block diagram is in Fig.2.

The transmitter is shown in Photo 1 and the lead image. This box includes an electret microphone driver, bias generator, voltage-to-current converter and the laser itself.

We have used a fixed bias for the laser diode that sets the current to about 20mA. This has proven sufficient to drive all the laser diodes we tried and keeps using the transmitter simple.

The combined bias and audio signal drive our voltage-to-current converter with five transistors implementing an operational amplifier (op amp) with buffer. We selected a Keyes unit for the laser diode. These are very commonly available as Arduino breakout modules.

We have included a screw jack on the base of the box using a 3⁄16-inch nut and bolt that we found in the shed glued to a PCB offcut (an M5 or M6 nut and bolt/machine screw would also work). This allows fine adjustment of the tilt of the transmitter, which is essential to align it with the receiver over longer distances.

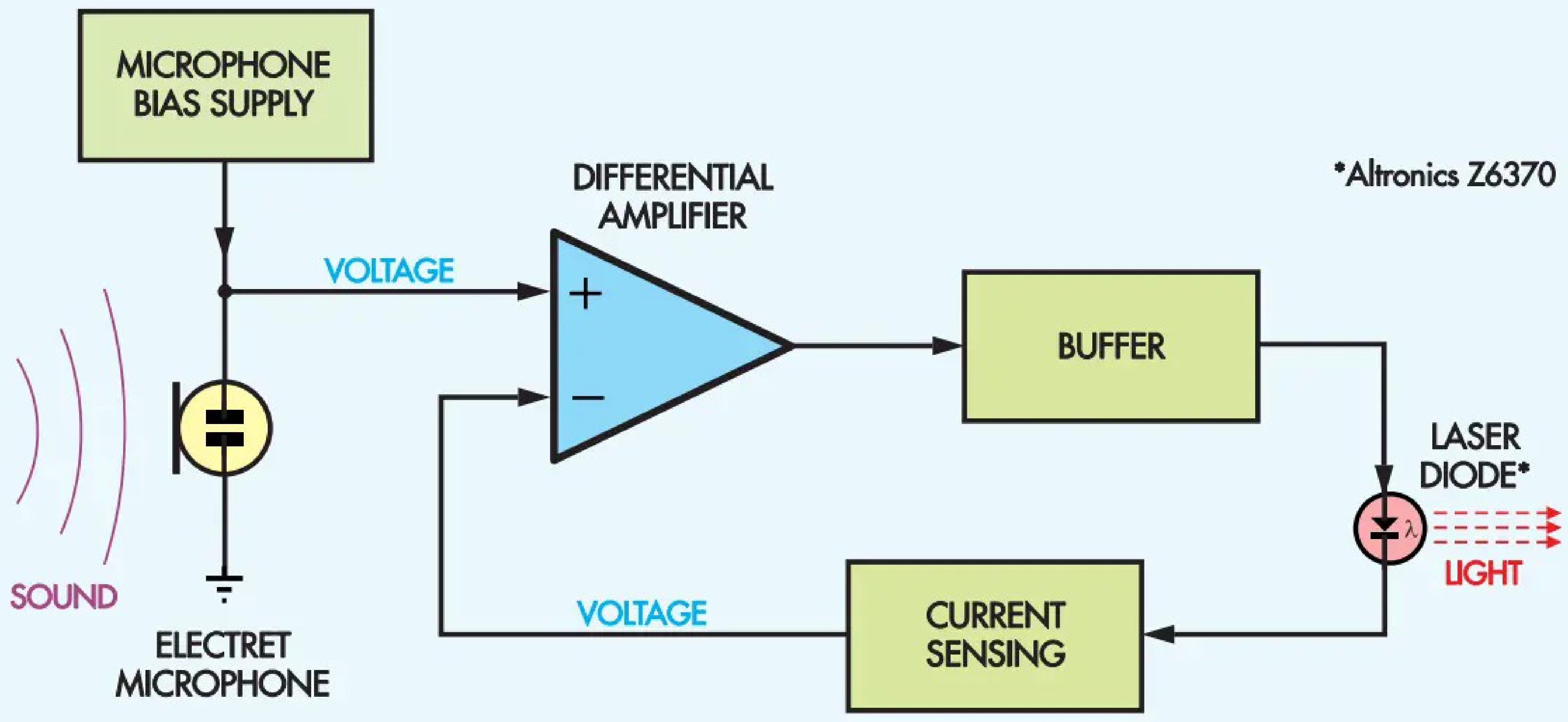


Fig.1: the modulator in the transmitter uses a differential amplifier set up as a voltage-to-current converter.

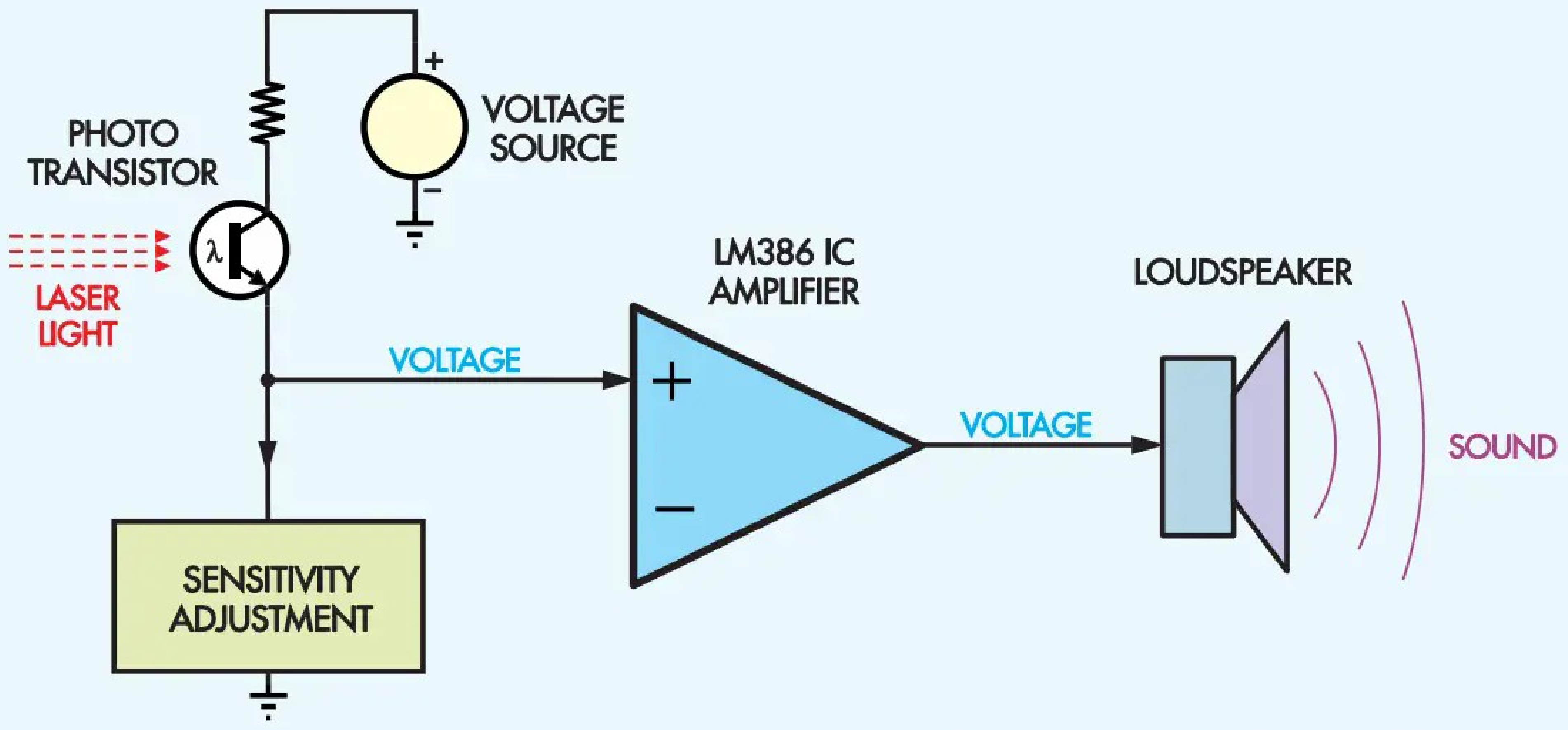


Fig.2: the receiver uses a phototransistor driving a LM386 IC amplifier, which in turn drives a 100mm loudspeaker.

The receiver is housed in a much larger box, as shown in Photo 2 and the lead image. This box includes the PCB with the phototransistor and amplifier as well as a 100mm loudspeaker. The receiver has a sensitivity control that doubles as a volume control.

The illumination level on the receiver will vary greatly over different ranges and depending on how well-aimed the laser is. That means the phototransistor must operate over a wide dynamic range of intensities. We achieve this by making the phototransistor's load resistance adjustable.

This also affects the volume, so there is no need for a separate volume control.

Even though we are running the laser at a low power, it is quite intense. We can use this fact to make aiming easier by sticking a piece of white paper over the receiver hole in front of the phototransistor. We put a target on this so we had a clear aim point.

The benefits of this are twofold: we can see exactly where to aim, and the paper diffuses the laser light into the inside of the receiver box, which spreads it onto the phototransistor even if the aim is not exact. We found that to be the best way to make it work even over pretty long ranges.

Transmitter circuit details

The transmitter circuit is shown in Fig.3. It uses an electret microphone, which converts sound into an electrical voltage. At normal 'voice levels', its output signal is a few hundred millivolts. If you want to use a phone or other line-level input to drive this link, you can omit the leftmost 4.7kΩ resistor and replace the microphone with a 3.5mm jack socket.

We are coupling the electret to the differential amplifier via a 100nF capacitor. This fairly low value was selected as younger users tend to talk right into the microphone, which would cause a lot of popping and saturate the laser link if a higher value were used.

Caution: Class 2 Laser

- *Do not stare into the beam.*
- *This power level is safe for unintended exposure for less than 0.25 seconds (250ms).*
- *Never view the laser using telescopic optics.*

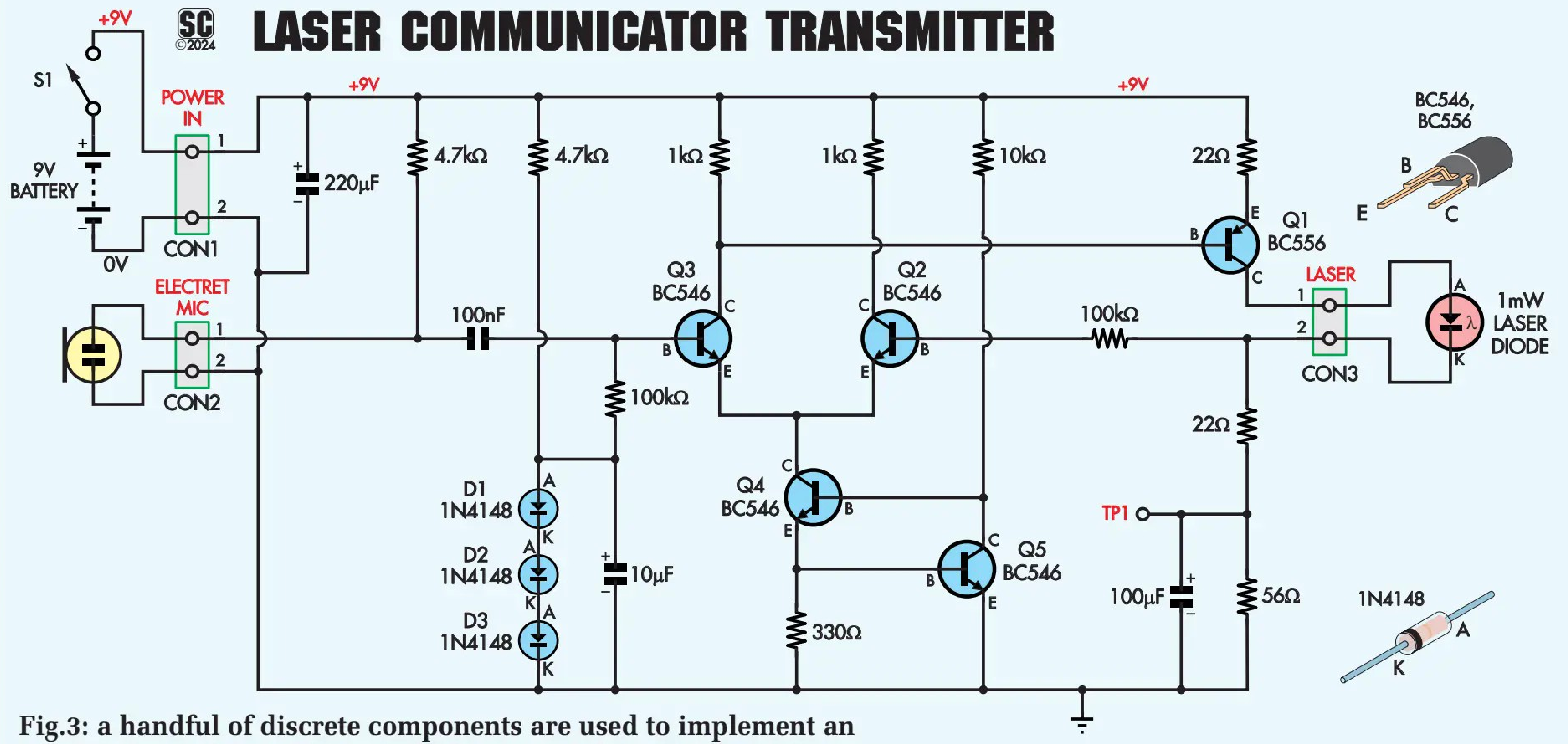


Fig.3: a handful of discrete components are used to implement an amplitude-modulated laser with direct modulation of the drive current.

We made a simple handheld microphone using an empty ballpoint pen case. While basic, this works well, and Zak really enjoyed gluing and shrinking it all together. He also learned that super glue on your fingers is very sticky! More on how we did that later.

Photo 2: the receiver box doubles as the speaker baffle. The Post-it note with a target drawn on it is important, as it gives you something to aim at and spreads the laser light, making the link easier to set up (masking tape also works).

We want to modulate the laser diode amplitude with the audio voltage. Laser diodes need to be driven by a current source, rather like LEDs, which means that we cannot simply connect the microphone to the laser. Furthermore, as shown in Fig.4, laser diodes have a threshold current below which they do not lase, so we need reasonable control over this.

We convert the microphone voltage to a laser current using a differential amplifier. The non-inverting input is fed with the microphone voltage imposed on a bias voltage, while the inverting (feedback) input is a voltage derived from the current through the laser diode. The laser current is converted to a feedback voltage by a resistance in series with the laser diode.

The five transistors form a differential amplifier as follows. NPN transistors Q4 and Q5 act as a constant current sink, pulling a fixed current from the junction of the emitters of NPN transistors Q2 and Q3.

Those two transistors act as the voltage comparator; as their total emitter current is fixed, whenever one conducts less current, the other must conduct more. The one with the higher base voltage of the two will pass more current than the other, as it will have the higher base-emitter voltage (because the emitters are joined).

PNP transistor Q1 is the output buffer that drives the laser. Note how the collectors of Q2 and Q3 both connect to the same +9V rail via 1kΩ resistors. That means any extra current needed for Q3 (when Q2 is conducting less) will tend to come from the base of Q1, so its base current is related to the difference in the two input voltages.

When Q3 conducts more, Q1 switches on harder, and when Q3 conducts less, Q1 starts to cut off.

The active current sink comprising Q4 and Q5 is probably unnecessary. Still, this current controls the maximum laser current, and we want to ensure it is consistent as the battery discharges and its terminal voltage drops.

The 330Ω resistor sets the tail current for the differential pair to 1.8mA, so about 0.9mA through each of the two 1kΩ collector resistors for Q3 & Q4 (although Q3 normally conducts a little more than Q2).

The DC bias point for the laser diode is set by the three 1N4148 diodes, which will have a combined forward voltage drop of 1.8V. In the absence of a signal, and as the average of an AC signal, the DC voltage on the base of Q3 is set by this via the 100kΩ resistor. There is a DC base current for Q3 of about 40µA, so the bases of Q2 and Q3 sit at about 1.4V.

A feedback loop is created around Q2 and Q3, with the base of Q2 driven through the 100kΩ resistor that senses the cathode voltage of the laser diode. The cathode current goes to ground

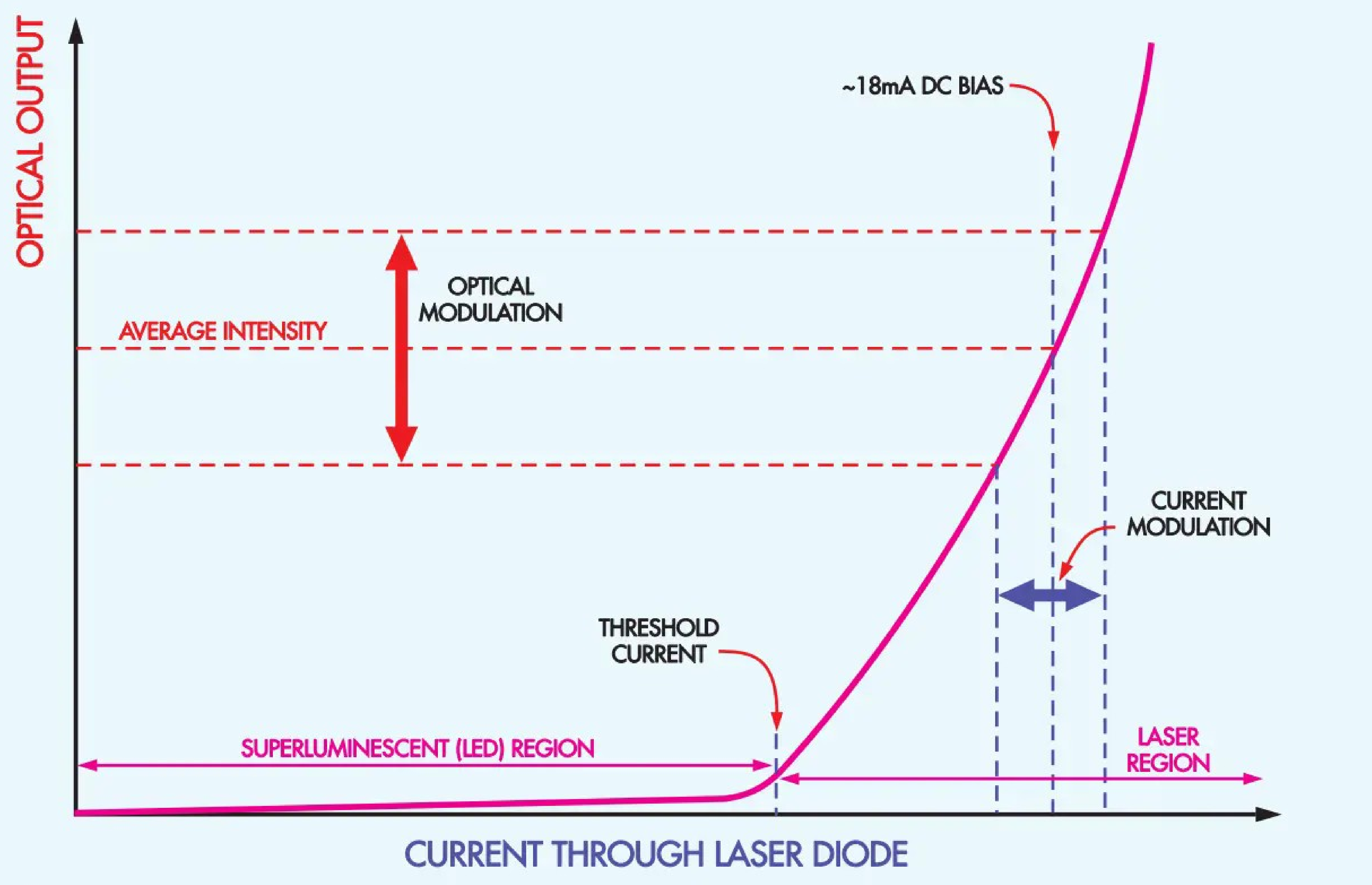


Fig.4: the laser optical output as a function of input current. Laser diodes do not operate as a laser until they have sufficient current flowing through them, so we need to set a minimum bias current when modulating the power to the laser.

through 22Ω and 56Ω resistors. The feedback loop keeps the base voltages of Q2 and Q3 the same, so the average voltage across these two resistors is 1.4V. Thus, the DC bias current for the laser diode is 18mA (1.4V ÷ [22Ω + 56Ω]).

All the laser diodes we tested had a threshold current much less than that, so they operated without adjustment in this circuit. If, for some reason, your laser diode is way too dim and everything else in the circuit is correct, the laser bias point can be altered by reducing the value of the 56Ω resistor.

Be very careful doing that, though, as you could create laser intensities that exceed Class 2, which is unacceptable without eye protection.

The keen-eyed will note a 100μF capacitor in parallel with the 56Ω resistor. It increases the system's AC gain, allowing us to get double service from the voltage-to-current amplifier. It provides about 11dB of extra gain for audio signals.

The AC laser current is 45mA/V. The maximum input voltage before clipping is about 500mV peak.

Receiver circuit details

As shown in Fig.5, the receiver uses a simple phototransistor with a resistive load to detect the incident laser radiation.

Because we are amplitude modulating the laser, the output of this detector contains both the DC bias on the laser and the AC content that we have modulated on top.

Because the phototransistor acts like a diode that responds only to the intensity of incident light, ignoring the carrier frequency, it also demodulates the signal.

The current through the phototransistor develops a voltage across potentiometer VR1. This voltage includes a DC component (the average intensity of the laser signal) and an AC component (the modulated audio waveform).

If the phototransistor's load resistance (VR1) is too high, the laser DC bias from the transmitter will saturate it. This will be seen as the voltage on the phototransistor collector increasing until clipping occurs. At high intensities, VR1's resistance can be reduced to avoid saturation of the photodetector.

This allows us to set the receiver's sensitivity to the intensity of incoming laser light while also acting as a volume control. The 330Ω resistor is in the circuit so that if VR1 is set to zero, the phototransistor still has a 330Ω load rather than being shorted across the battery.

We have AC-coupled the signal to the input of a venerable LM386 power amplifier, IC1. This is used in pretty much a textbook configuration. We have minimal bypassing on pin 7 as we have battery power, so there should be little rail noise.

We have used the gain setting pins (pins 1 and 8) to set a reasonably high

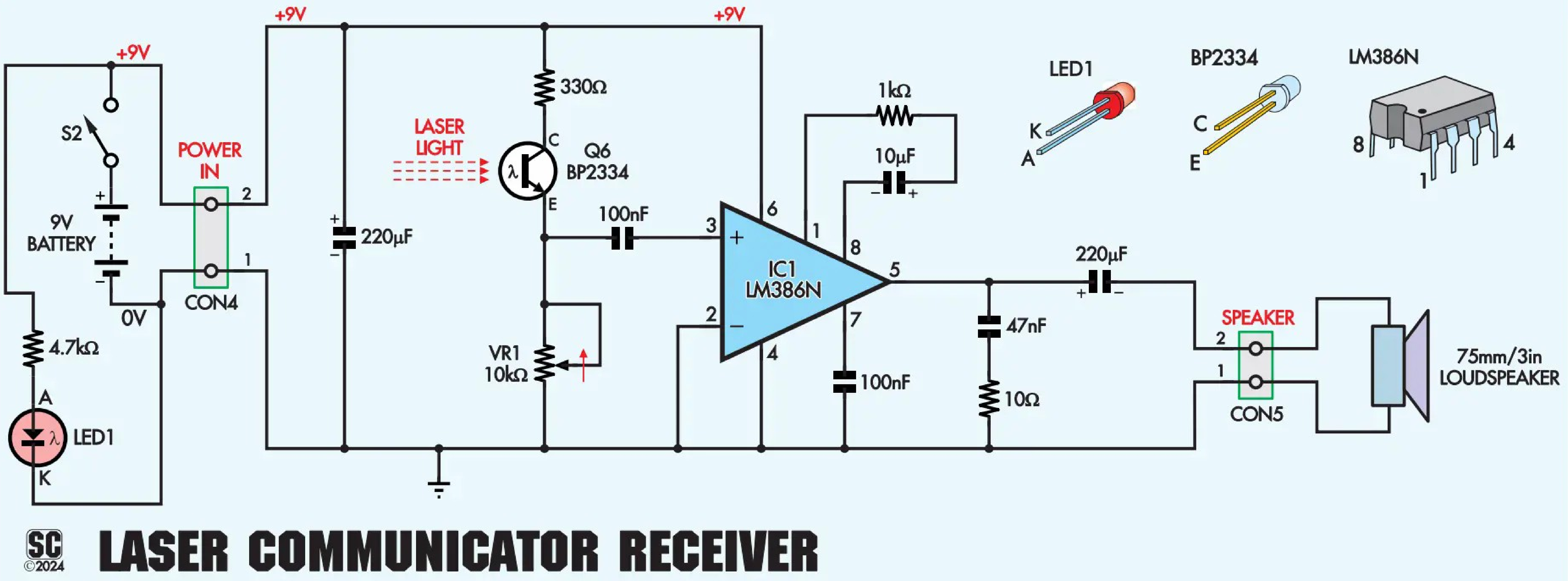
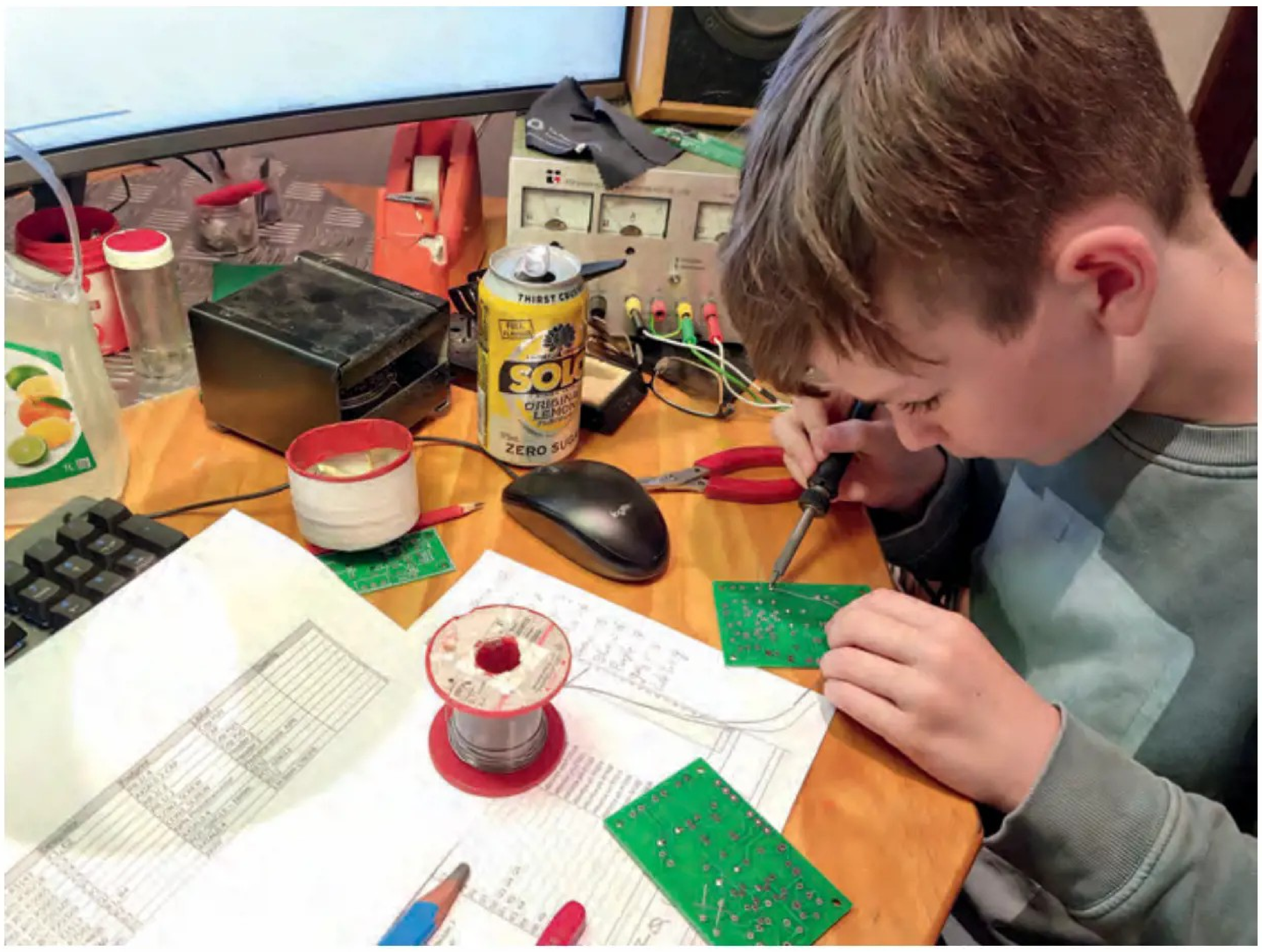


Fig.5: the receiver is straightforward, utilising an old-school LM386 power amplifier driven by a phototransistor.



◄ **Photo 3: we got some user feedback on the prototype build, resulting in some tweaks to the design and layout to make it more approachable for all builders. I built the two units simultaneously with Zak so he could watch how I did it, but I let him build his own.**

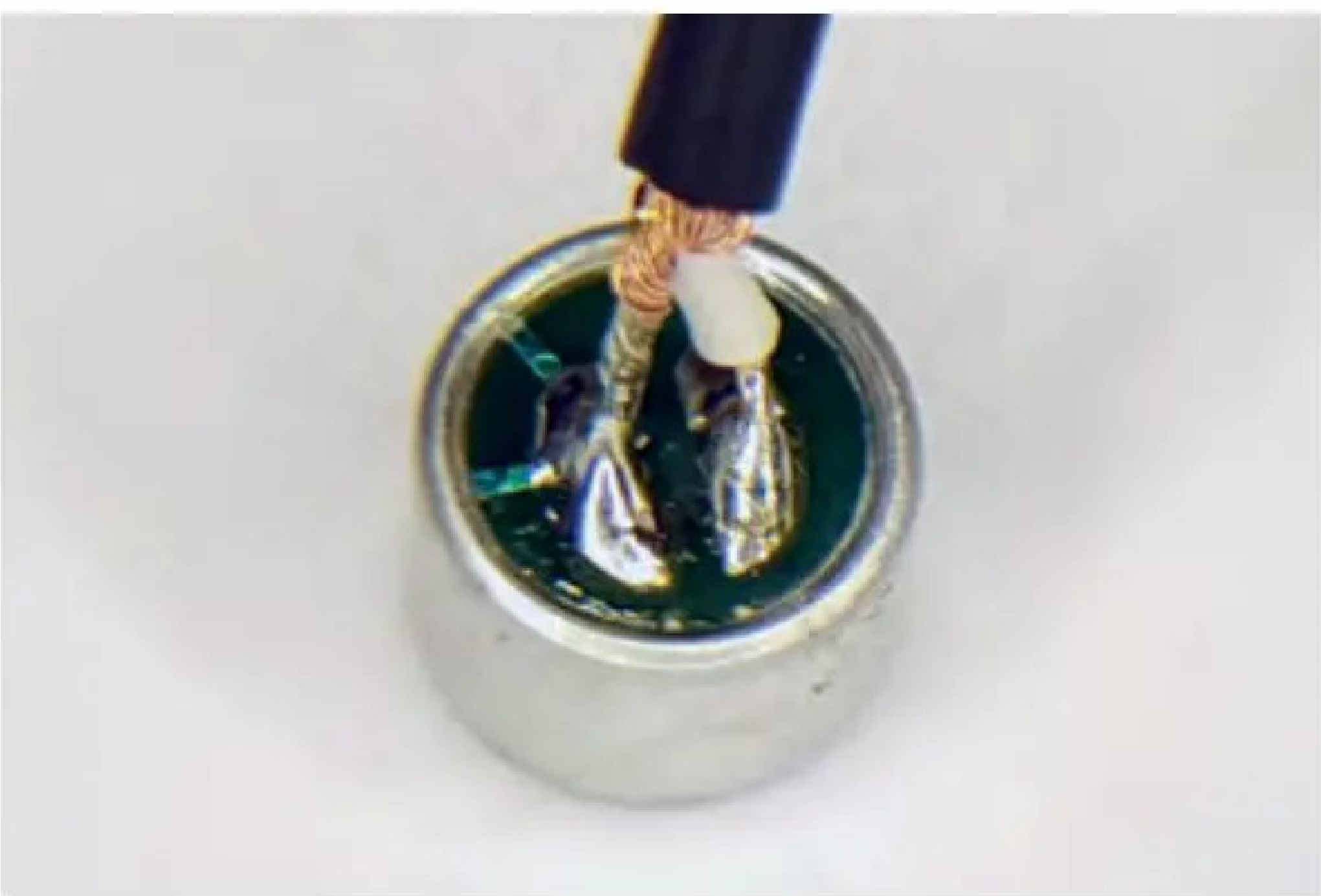


Photo 4: this shows how the shielded cable is soldered to the electret microphone insert. The screen braid goes to the pad connecting to the mic case.

gain. If you need to reduce the receiver's gain, you can increase the value of the 1kΩ resistor.

We have specified a 100mm speaker for this project and recommend that it be mounted in a UB3 Jiffy box. Doing so is necessary to achieve decent efficiency and sound output from the receiver.

One of our initial prototypes used a much larger hifi speaker, which worked a treat. So if you wish to build a 'bare' version of this project, wiring the receiver's output to a large speaker is a good option.

We found that using a tiny 57mm speaker without a box was pretty disappointing, so avoid that.

Construction

The wide layout and large pads make this an ideal starter project (see Photo 3). The intention was to make it approachable to people of all experiences with a little guidance. We won't reiterate how to solder as we expect that most readers will have at least some experience doing so.

The process for the two boards is similar. Fig.6 is the transmitter's overlay diagram, which shows where each component goes, while Fig.7 is a similar diagram for the receiver.

In each case, start with the resistors. Check the values as you go; if you are unsure, use a multimeter to check their values. We used this as a chance to show our youngster how to decode resistors. The transmitter has eleven resistors, while the receiver has only three. Either way, check them against the marked values on the PCB. We start with these as they are the 'flattest' parts.

Next, install the three diodes on the transmitter board. Make sure they are the right way around, or the transmitter won't work.

We have specified the 1N4148 (a common type, similar to the 1N914 but with lower leakage), but you could use just about any silicon diode. Still, it's better to stick with the parts that we've tested.

Next, mount the capacitors. We have

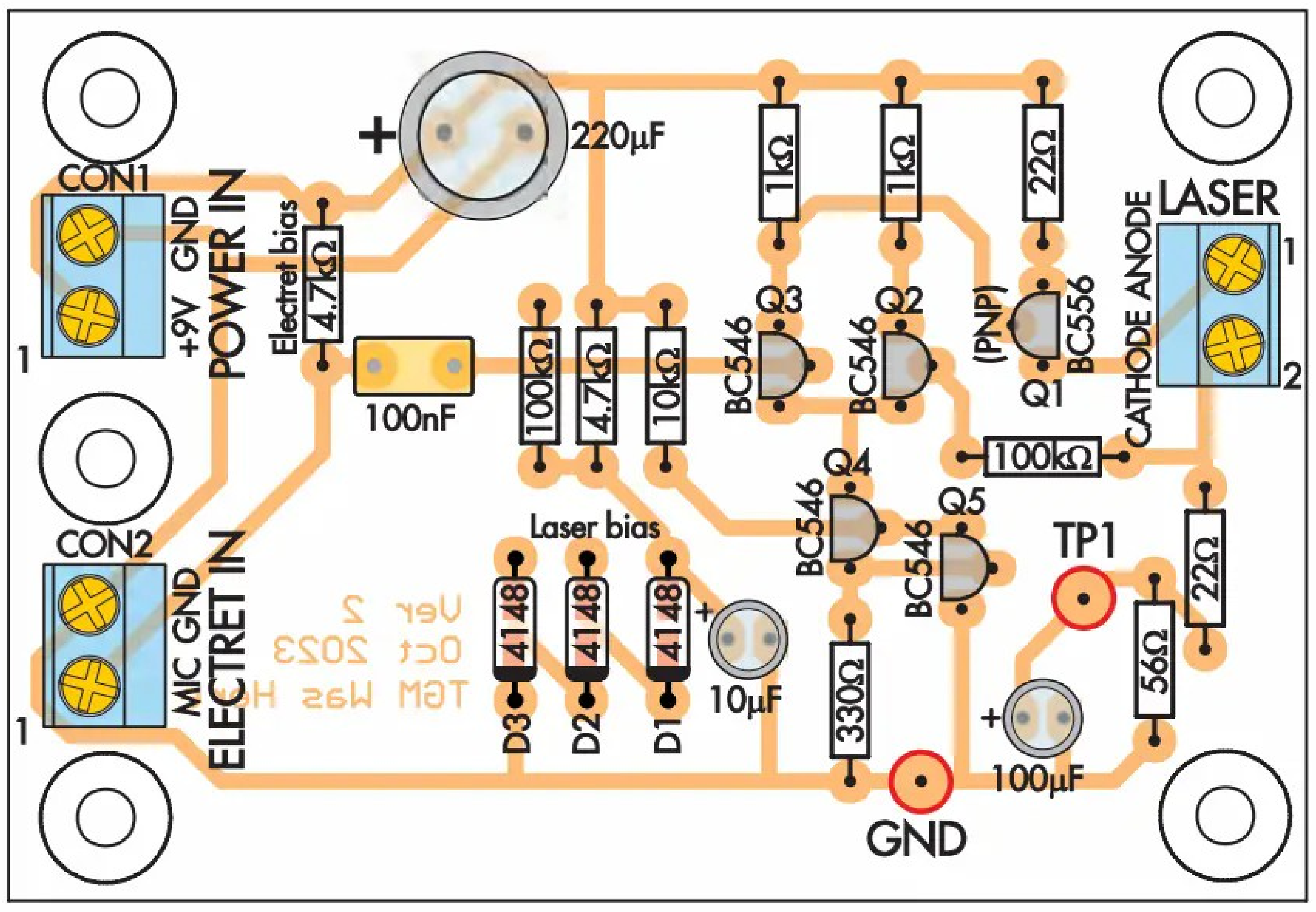

CON1
+9V GND
POWER IN
1
Electret bias
4.7kΩ
+
220µF
100nF
100kΩ
4.7kΩ
10kΩ
1kΩ
1kΩ
22Ω
BC546
Q3
BC546
Q2
(PNP)
BC556
Q1
LASER
CATHODE ANODE
1
2
100kΩ
CON2
MIC GND
ELECTRET IN
1
Laser bias
D3 4148
D2 4148
D1 4148
+
10µF
BC546
Q4
BC546
Q5
330Ω
TP1
22Ω
56Ω
+
100µF
GND

Fig.6: here's where to solder the components on the transmitter board. For the electrolytic (can-type) capacitors, ensure the longer leads go into the holes marked with + symbols. The transistors have flat faces that are orientated as shown here.

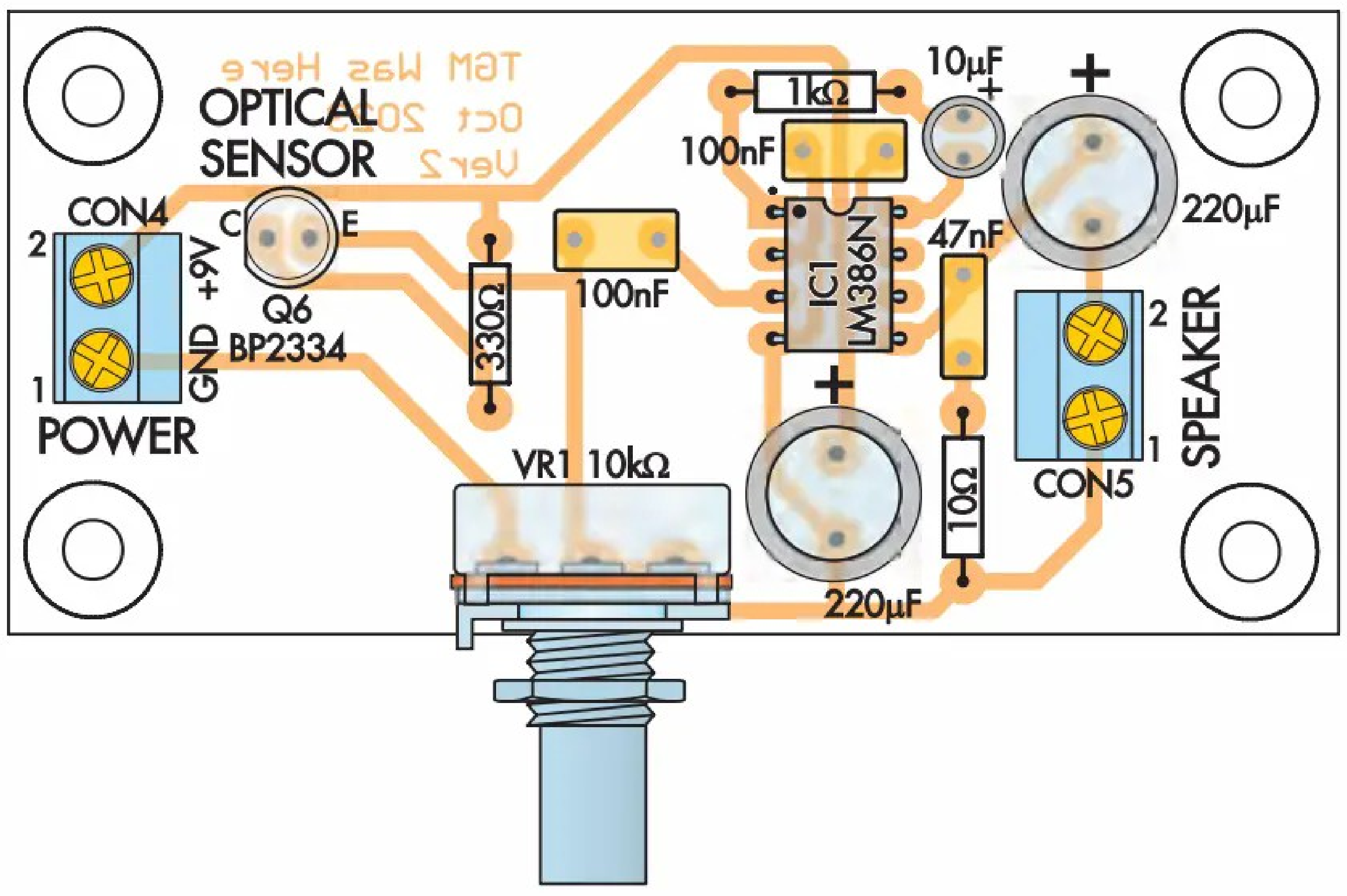
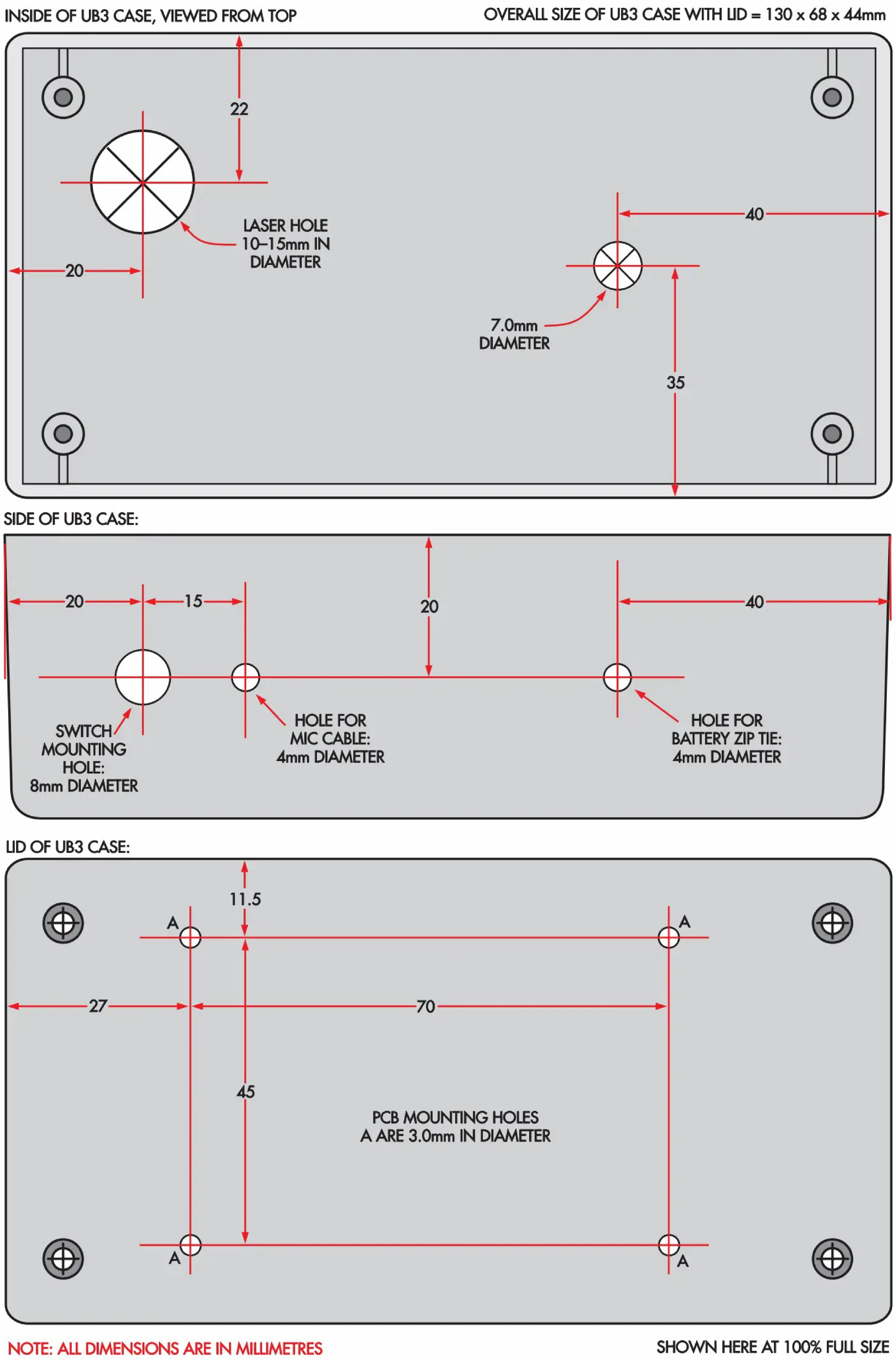

OPTICAL
SENSOR
CON4
2
+9V
GND
1
POWER
C
E
Q6
BP2334
330Ω
100nF
1kΩ
100nF
10µF
+
IC1
LM386N
47nF
+
220µF
+
2
1
CON5
SPEAKER
VR1 10kΩ
10Ω
220µF

Fig.7: similarly, fit the components for the receiver like this. The IC will have a dot or other indicator for pin 1, which has to go at upper left. Like with the transmitter, be careful with the orientation of the electrolytic capacitors and also the phototransistor sensor, Q6.

Fig.8: the transmitter lid drilling is straightforward, with just four 3mm holes to drill in a rectangular pattern for mounting the PCB. The transmitter base needs just two holes drilled, with the larger one sized to suit the laser diode, plus a further three holes in the side.


INSIDE OF UB3 CASE, VIEWED FROM TOP
OVERALL SIZE OF UB3 CASE WITH LID = 130 x 68 x 44mm
22
20
LASER HOLE 10–15mm IN DIAMETER
40
7.0mm DIAMETER
35
SIDE OF UB3 CASE:
20
15
20
40
SWITCH MOUNTING HOLE: 8mm DIAMETER
HOLE FOR MIC CABLE: 4mm DIAMETER
HOLE FOR BATTERY ZIP TIE: 4mm DIAMETER
LID OF UB3 CASE:
11.5
A
A
27
70
45
PCB MOUNTING HOLES A ARE 3.0mm IN DIAMETER
A
A
NOTE: ALL DIMENSIONS ARE IN MILLIMETRES
SHOWN HERE AT 100% FULL SIZE

ensured that all the electrolytic capacitors face in the same direction, but double-check them as, if they are the wrong way around, bad things will happen.

Follow by soldering in the transistors on the transmitter. Q1 is the PNP type (eg, BC55x), while the remainder are NPN types (BC54x). You can happily use BC556/7/8/9 for the PNP and BC546/7/8/9 for the NPN. The main thing to watch for is that you do not get the two types mixed up.

Now mount the LM386. You might need to squeeze the pins in a bit to get it to fit. This is a tough old chip, so don't be afraid of giving it a squish to get it in.

Finally, mount the potentiometer on the receiver PCB, along with all of the screw terminals. Use a logarithmic potentiometer here; a linear pot will work but will be more fiddly to adjust.

Now install the laser diode. We bent the middle leg of our laser diode module out straight; the remaining legs slot straight into the screw terminal. The "S" marked on the module indicates the anode or positive lead, while "–" indicates the cathode or negative.

If you have a different laser diode, you can check which is the anode and which is the cathode using a 9V battery with a 4.7kΩ resistor connected in series (you have one of these for your power LED). The laser will light up when the anode is wired to the positive battery terminal. Don't forget the resistor, or you could burn it out!

Wiring advice

We have wiring diagrams over the page, so refer to them once we get to that stage. But first, here is some advice.

The flying leads of the battery clips will form a fair bit of your wiring. Any other power wiring can be done with light-duty hookup wire.

The power LED for the receiver comprises a red LED and a 4.7kΩ current-limiting resistor. Make sure that the anode of the diode (longer lead) is wired to the switched 9V

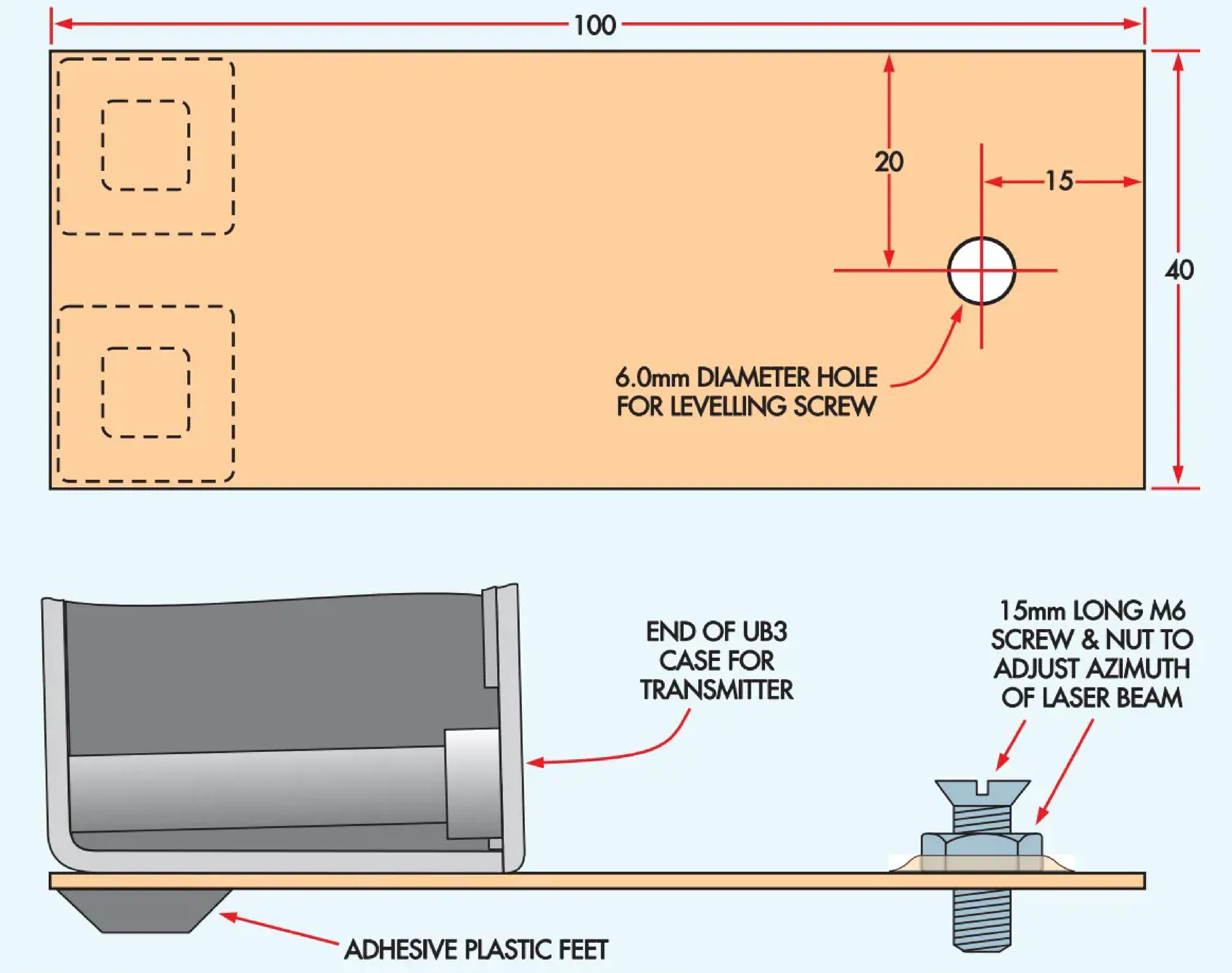

100
20
15
40
6.0mm DIAMETER HOLE FOR LEVELLING SCREW
END OF UB3 CASE FOR TRANSMITTER
15mm LONG M6 SCREW & NUT TO ADJUST AZIMUTH OF LASER BEAM
ADHESIVE PLASTIC FEET

Fig.9: gluing a nut to the base and threading a screw into it allows you to easily adjust the angle of the case relative to the ground in small increments so you can aim the laser precisely.

input, while the resistor goes from the anode of the LED to the ground pin on the power input.

The microphone input should be made using shielded cable; we used about a metre of it. Connect the braided screen to the electret ground. This pin connects to the case of the electret, which is visible on the back of the microphone capsule (see Photo 4).

Solder the cables's inner conductor to the electret's output (the other pad). The screen of this cable goes to the GROUND terminal of the microphone connector on the transmitter board, while the inner core goes to the MIC terminal.

We used an old ballpoint pen case as a handle for the microphone by running the coaxial cable through the middle of it, then soldering the electret on top. We eventually ended up gluing it in place with super glue. This gave us a simple microphone at minimal cost.

To make the microphone look neat and for some fun, we put 10mm heatshrink tubing over the whole microphone, down to the cable. If you don't have a hot air gun to shrink it, many hairdryers are hot enough to work.

Housing the boards

Assembly into the cases is optional, but we really recommend it. We are providing drilling diagrams that will allow you to assemble the transmitter and receivers into tidy boxes.

For the transmitter, mark and drill the holes in the case lid, as shown in Fig.8. Check the location of your marks by placing the PCB on them before drilling. Next, mark and drill the holes in the base, also shown in Fig.8. That includes holes for the power switch, microphone lead and a zip tie (cable tie) to hold the battery still.

Now mark and drill the laser output hole. The laser hole can be anything large enough to ensure you can get the laser out.

Run the microphone cable through its hole, mount the switches and terminate the leads on the transmitter board. Use 10mm M3 standoffs, 6mm screws and shakeproof washers to mount the PCB to the top of the case.

Make a screw jack base for the transmitter, as shown in Fig.9. Our baseplate was 100mm long and 40mm wide, though anything will do that allows you to adjust the tilt of the transmitter. We glued a nut to our

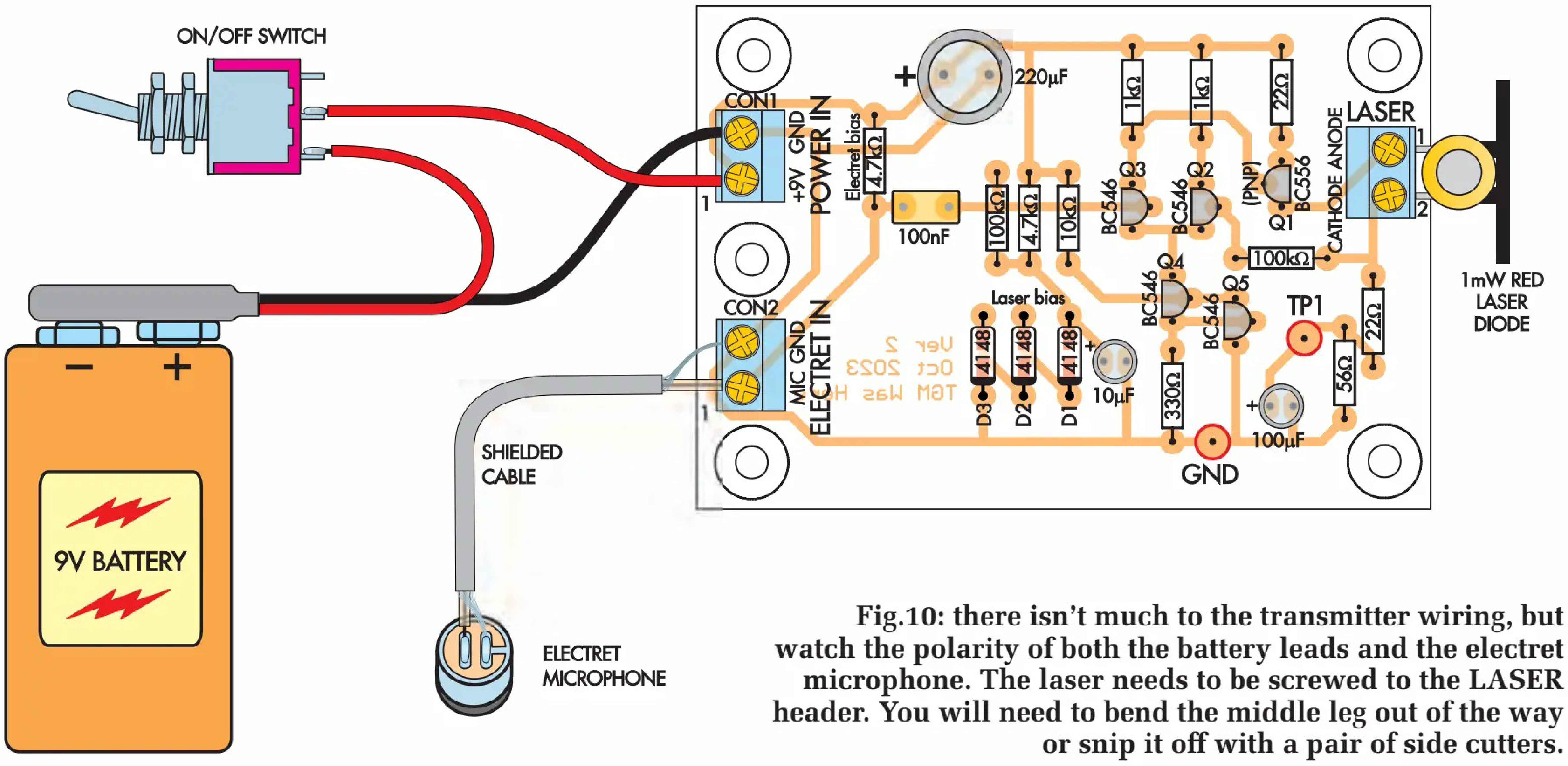

ON/OFF SWITCH
9V BATTERY
SHIELDED CABLE
ELECTRET MICROPHONE
CON1
+9V GND
POWER IN
CON2
MIC GND
ELECTRET IN
Electret bias
4.7kΩ
220μF
100nF
100kΩ
4.7kΩ
10kΩ
1kΩ
1kΩ
22Ω
BC546
Q3
BC546
Q2
(PNP)
BC556
Q1
CATHODE ANODE
LASER
Laser bias
4148
D3
4148
D2
4148
D1
10μF
BC546
Q4
BC546
Q5
100kΩ
TP1
22Ω
330Ω
56Ω
100μF
GND
TGM Laser H
Oct 2023
Ver 2
1mW RED LASER DIODE
1
2

Fig.10: there isn't much to the transmitter wiring, but watch the polarity of both the battery leads and the electret microphone. The laser needs to be screwed to the LASER header. You will need to bend the middle leg out of the way or snip it off with a pair of side cutters.

stand so a screw or bolt could be used as a screw jack.

Glue the screw jack base to the base of the transmitter box. Sand the ABS plastic so that your glue sticks well. We roughened the base of the case with sandpaper and used Araldite to glue the nut onto the screw jack. Sanding the base gives the Araldite a good surface to adhere to. Make sure you have good ventilation while it cures.

Finally, stick rubber feet to the front of the screw jack.

Transmitter wiring

There is just a little bit of wiring to do, as per Fig.10. You can use any colour wires you choose, but we recommend red and black for the battery and switch wiring.

For the microphone, we ran the coax through the case and tied a knot inside as very low-cost strain relief, ensuring that any enthusiasm from young users does not tear the microphone cable from the terminal on the transmitter board.

Receiver case assembly & wiring

Mark and drill the holes in the lid, as shown in Fig.12. There are two holes in the main case for the zip tie to secure the battery; see Fig.13.

The speaker hole might be fiddly to cut. We used a circle saw for ours. ABS plastic is very soft, so a handsaw will do this job easily. This is one task that is best undertaken by an adult if working with young constructors.

More tips for kids from a kid!

What was important when assembling the boards?

- *Working out which part needs to go on the board.*
- *Searching for the numbers on the board and working with an adult to make sure I had the right parts.*
- *Learning to 'decode' the resistor codes, to check that an adult had given me the right bits.*

Some soldering tips, how to do it and tricks for people to know:

- *Keep the iron's tip away from people!*
- *Go slow; remember not to rush soldering each joint.*
- *Remember where to put the tip of the iron. Put the soldering iron on one side of the joint and put the solder on the other side.*
- *Also, it's fun just to melt the solder!*

Do you have any tips for putting heatshrink tubing on wires?

- *Don't point the hot air gun at people or their fingers (and watch your fingers when helping!)*
- *Take your time while doing it so that you shrink the tube fully.*
- *Don't put the tip of the hot air gun right on top of the heatshrink. There needs to be a gap.*

Tips on drilling the box

- *Wear safety glasses for protection, and never turn a drill on with your fingers near the bit.*
- *Put tape where you will drill and mark it with a pen.*
- *Hold the parts tight when you drill them. Keep your hand tightly on the box when drilling small holes in the box.*

Putting stuff in the box:

- *Make sure the box is drilled properly with the holes where they belong. Phil helped with this.*
- *Put stuff in spots it can fit, and get some help.*
- *Keep stuff steady when you put a zip tie or nuts and bolts on.*

Using the communicator:

- *Don't put the boxes too far away from each other because it's harder to line up (it was pretty tricky at 15m apart).*
- *Don't put the microphone right in your face when talking or put it too far away.*
- *You do not need to shout.*
- *To play music over the link, you play a song of your choice and put the small speaker of the phone or whatever you use against the microphone. This works really well.*

Are there any other cool things?

- *Waving your hands in the beam makes some really interesting sounds.*
- *Waving a strainer through the beam makes even crazier sounds.*
- *Putting your hand in the beam totally stops the sound.*

How to get it all lined up:

- *First, turn both boxes on.*
- *Look for the dot from the laser. It is bright and you won't miss it.*
- *Turn the screw to get the laser dot to go up and down until it is at the right height.*
- *Then move the box left and right until the dot is on the paper. You are all set to go!*

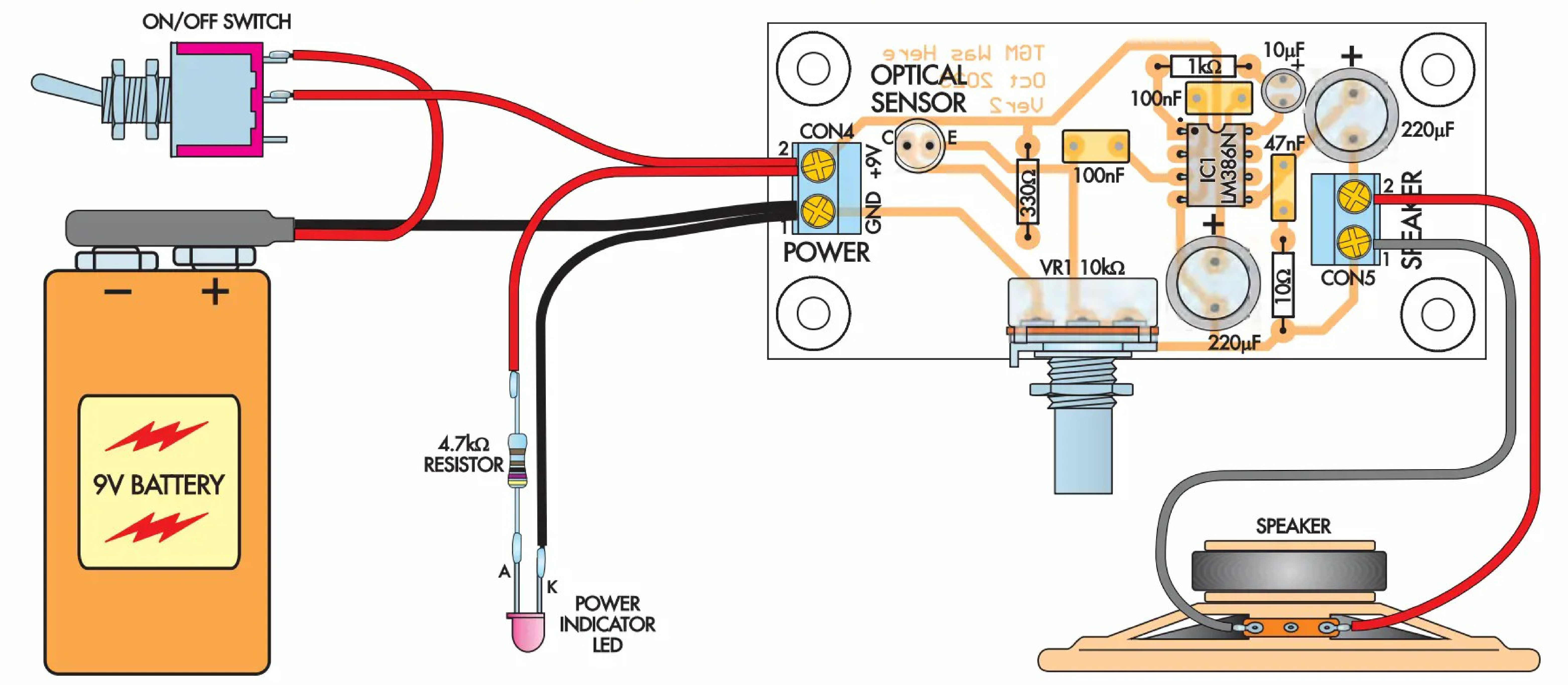


Fig.11: when wiring up the receiver, the speaker's polarity doesn't matter, but the battery polarity does, so check it. If you wire the LED incorrectly, it won't light up.

Next, drill the hole for the sensitivity pot and its locating pin, the photodetector hole, the power switch and the LED. Poke the LED through the 5mm hole in the case and use a dab of superglue to hold it in place.

Secure the power switch with its washer and nut. A large pair of pliers helps here, but can be fiddly for younger hands. Use 10mm M3 machine screws, M3 flat and shakeproof washers and nuts to secure the speaker.

Connect the battery, LED (with series resistor) and speaker to the receiver board, as shown in Fig.11.

Testing

First, check your wiring and ensure the black battery lead goes into the GND terminal of the power socket on both boards.

Turn the transmitter power on, and you should immediately see the laser light up. Measure the voltage at TP1 by setting your DMM into voltage measurement mode, connecting the red probe to TP1 and the black probe to GND. You should get a reading between 0.8V and 1.2V.

If the laser is not lit or the voltage on its cathode is out of the specified range, check that the laser has been connected the right way around. Put a meter across the laser diode on the mA range and measure the current. You should get a reading between 14mA and 22mA.

Also you should check the voltages across diodes D1-D3. There should be about 0.6V across each. If this is not the case, check that they are the right way around. Then make sure that the 10μF bypass capacitor is the right way around.

To verify that the current source is operating, check that the voltage on the base of Q5 (its middle pin) is about 0.6V relative to GND (its emitter) and that the voltage on the base of Q4 (middle pin) is about 1.2V relative to GND. If these are not OK, verify that you have fitted the right transistors and that they are in the right way around.

The base-emitter voltages for transistors Q2 and Q3 should be about 0.6V. With the flat side towards you, the base is the middle pin and the emitter is on the right.

If they are wrong, check that the transistor types are correct and that they are the right way around. The voltages

Parts List – Laser Communicator (Transmitter)

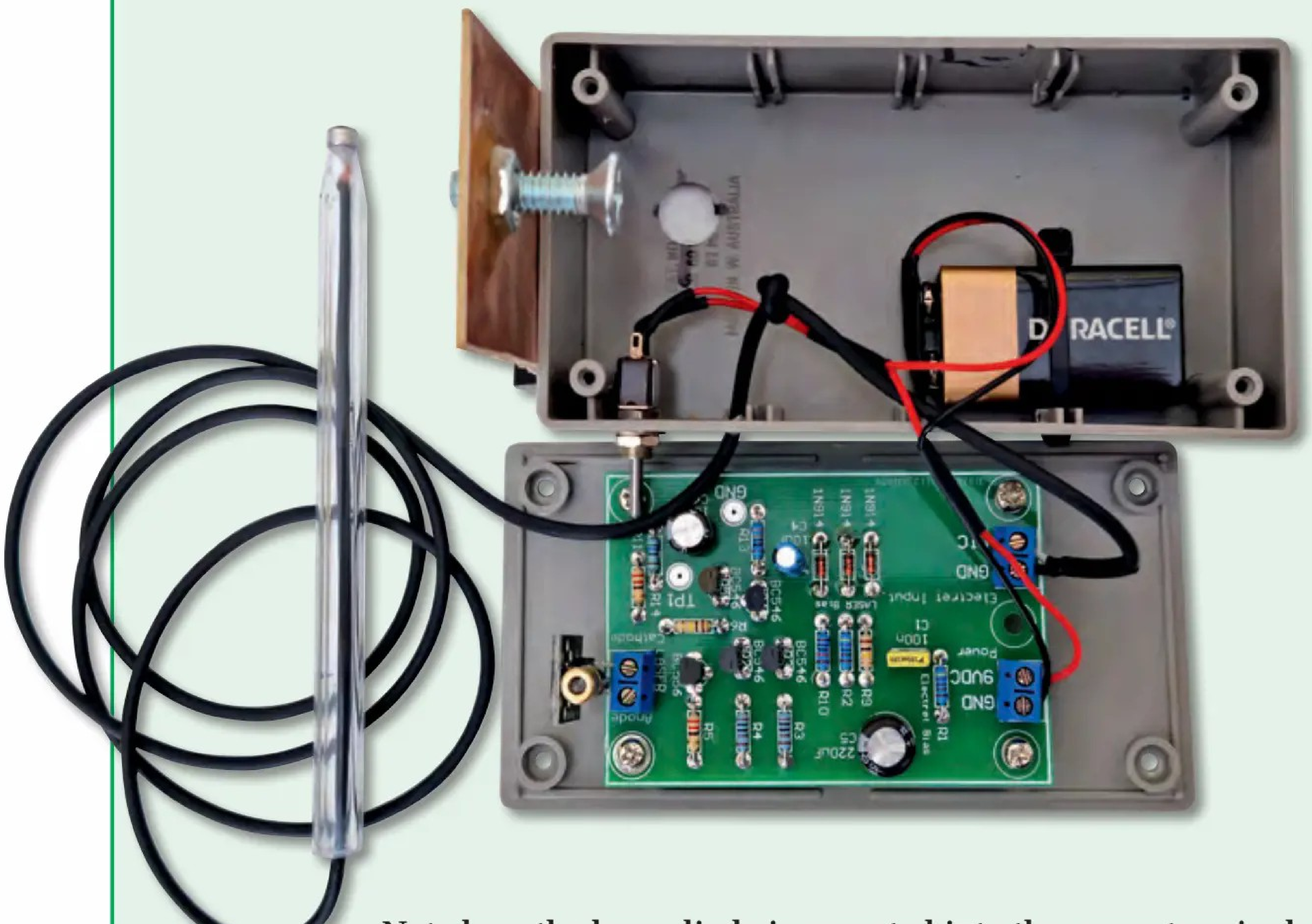
1 single- or double-sided PCB coded 16102241, 81.5 × 55.5mm
1 UB3 Jiffy box, 130 × 67mm
1 9V battery
1 9V battery clip with flying leads
1 1mW red laser diode module **[eg, AliExpress 1005006404528787]**
1 electret microphone capsule (MIC1)
1 solder tag mini toggle switch (S1)
3 2-way mini terminal blocks (CON1-CON3)
1 ballpoint pen case (to use as a microphone case)

Semiconductors
1 BC556/7/8/9 100mA PNP transistor (Q1)
4 BC546/7/8/9 100mA NPN transistors (Q2-Q5)
3 1N4148 or similar signal diodes (D1-D3)

Capacitors
1 220μF 16V radial electrolytic
1 100μF 16V radial electrolytic
1 10μF 16V radial electrolytic
1 100nF 63V MKT

Resistors *(all ¼W 1%)*
2 100kΩ
1 10kΩ
2 4.7kΩ
2 1kΩ
1 330Ω
1 56Ω
2 22Ω

Hardware
1 M5 or M6 × 40mm panhead machine screw and hex nut
8 M3 × 6mm panhead machine screw
4 M3 × 10mm tapped spacers
8 M3 star washers (toothed type)
2 6mm-tall rubber feet
1 150mm cable tie
1 1m length of single-core screened cable
2 200mm lengths of light-duty hookup wire (red & black)
1 150mm length of 10mm diameter heatshrink tubing
1 100mm length of 3mm diameter heatshrink tubing
1 100 × 40mm PCB offcut



Note how the laser diode is mounted into the screw terminal block, with its third middle lead bent out of the way. You can also see how we used a ballpoint pen case to house the microphone capsule.

across the 1kΩ resistors should be close to 0.8-1V, with the one connected to Q2 being slightly lower than the other.

Receiver testing

Before switching it on, check your wiring and make sure that the battery is connected the right way around. Switch it on and measure the voltage between pins 4 (lower left) and 6 (one above lower right) of the LM386 IC; the reading should be very close to the battery voltage. If it is lower, check that the LM386 IC is the right way around and check your wiring and the switch.

Next, measure the voltage on pin 5 of the LM386 relative to the GND terminal of CON4. This should be around half the battery voltage. If not, check that the electrolytic capacitors in the upper-right corner of the board are the right way around.

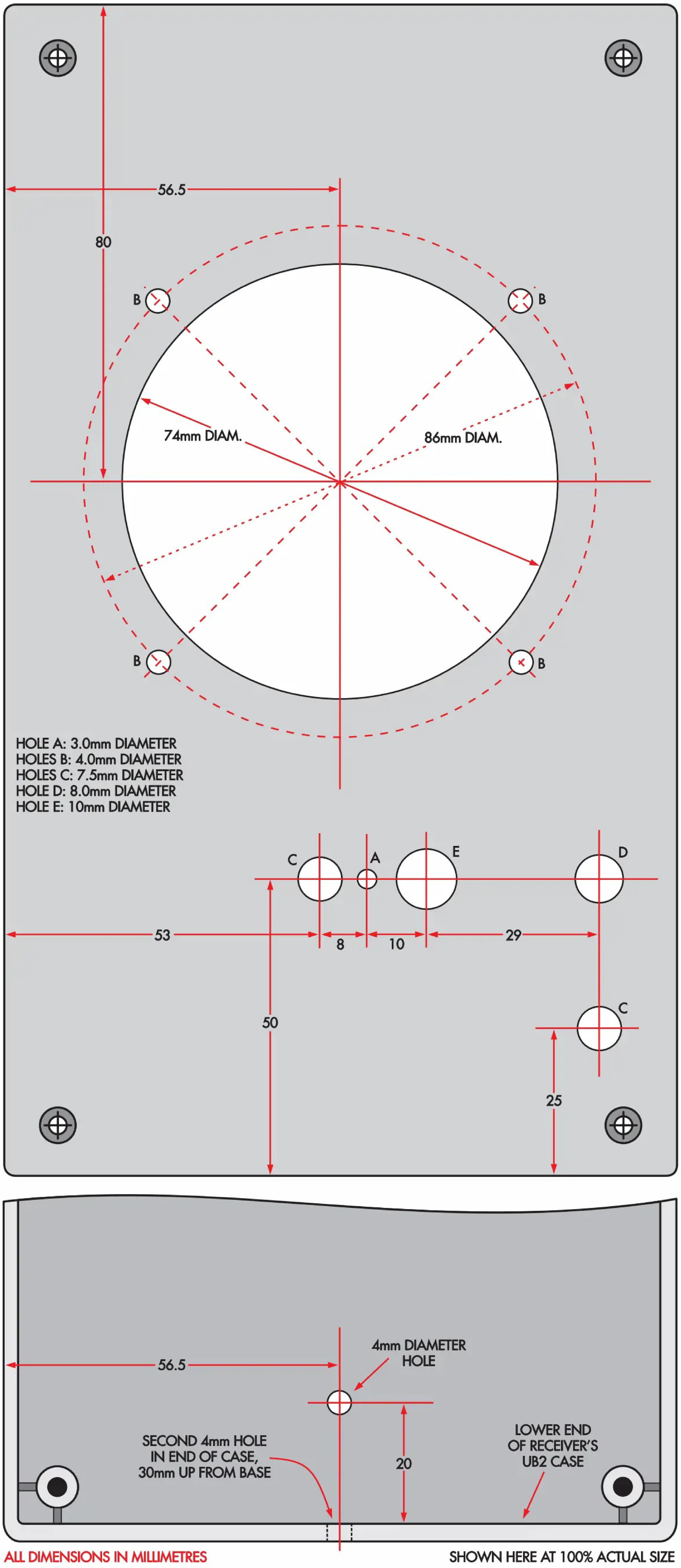
My LED bench lamp causes substantial buzz when it is close to the phototransistor, and even LED room lights cause buzz at maximum gain. Such buzz indicates that the circuit is working. Try this with a mains-powered LED light in your house or lab. If that doesn't work, check that the photodiode is the right way around.

If the above works, move on to the setup stage. Otherwise, as a final test, monitor the voltage on the middle pin of the potentiometer with a voltmeter and turn the sensitivity pot up and down from minimum to maximum. In that case, you should see the DC voltage vary, especially if the phototransistor is illuminated.

With the speaker connected, you could inject an audio signal of about 10-100mV at 1kHz (AC-coupled!) into the middle pin of the potentiometer with the volume turned right up. You should hear a loud (possibly distorted) tone from the speaker.

Setup

To set the system up, switch both the transmitter and receiver on, with them


56.5
80
B
B
B
B
74mm DIAM.
86mm DIAM.
HOLE A: 3.0mm DIAMETER
HOLES B: 4.0mm DIAMETER
HOLES C: 7.5mm DIAMETER
HOLE D: 8.0mm DIAMETER
HOLE E: 10mm DIAMETER
C
A
E
D
53
8
10
29
50
C
25
56.5
4mm DIAMETER HOLE
SECOND 4mm HOLE IN END OF CASE, 30mm UP FROM BASE
20
LOWER END OF RECEIVER'S UB2 CASE
ALL DIMENSIONS IN MILLIMETRES
SHOWN HERE AT 100% ACTUAL SIZE

Figs.12 & 13: the receiver lid drilling (top diagram) is the most complicated of the project, with one large cut-out for the speaker that we made with a hole saw, plus six smaller holes to drill. Shown in the bottom section of the diagram are the locations of two holes that a cable tie passes through to hold the 9V battery in place.

Parts List – Laser Communicator (Receiver)

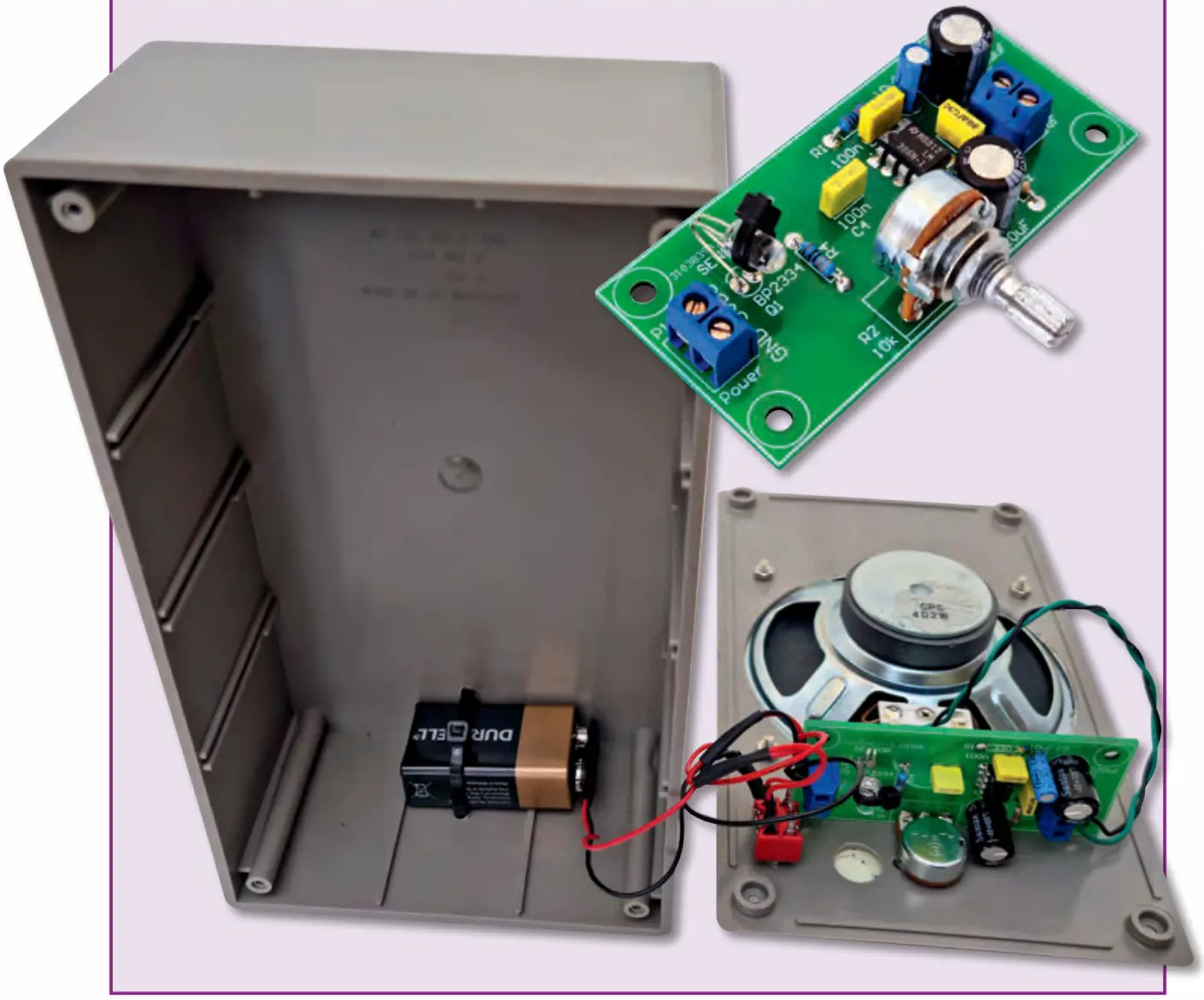
1 single- or double-sided PCB coded 16102242, 80 × 37.5mm
1 UB2 Jiffy box, 197 × 112mm
1 100mm loudspeaker driver **[eg, Farnell 2787070]**
1 solder tag mini toggle switch (S2)
1 9V battery
1 9V battery clip with flying leads
2 2-way mini terminal blocks (CON4, CON5)
1 10kΩ 16mm single-gang logarithmic taper potentiometer (VR1)

Semiconductors
1 LM386N 1W audio amp IC, DIP-8 (IC1) **[Farnell 3116863]**
1 BP2334 or TEPT5600 phototransistor (Q6) **[Farnell 1458698]**
1 red 5mm LED (LED1)

Capacitors
2 220µF 16V radial electrolytic
1 10µF 16V radial electrolytic
2 100nF 63V MKT
1 47nF 63V MKT

Resistors *(all ¼W 1%)*
1 4.7kΩ
1 1kΩ
1 330Ω
1 10Ω

Hardware
4 M3 × 10mm panhead machine screws
4 M3 flat washers
4 M3 star washers (toothed type)
4 M3 hex nuts
4 6mm-tall rubber feet
1 150mm cable tie
2 200mm lengths of light-duty hookup wire (red & black)
1 100mm length of 3mm diameter heatshrink tubing



separated by at least a few metres. Align the laser onto the receiver. We always use this with a piece of paper with a target stuck over the hole for the phototransistor. That makes it so much easier to get a decent link and stops the laser from saturating the phototransistor.

To align it, get the laser in the general vicinity of the receiver target, then adjust the screw jack so the laser dot is at the right height. Do this without holding the top of the transmitter, as that will mess up your aim when you let go of the box.

Once the elevation of the aim is correct, gently change the laser's azimuth by nudging the screw jack left or right. Again, don't try to turn the transmitter by holding the Jiffy box, as everything will move when you let go. Just nudge it.

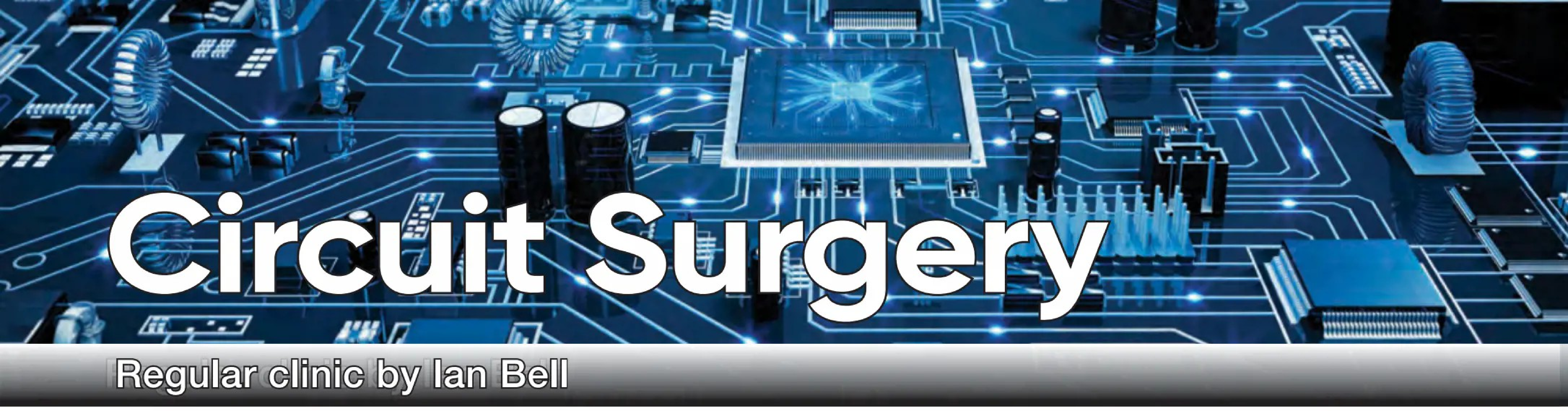
If the sensitivity is high enough, you should hear the receiver go quiet once the aim is good. Adjust the sensitivity from minimum up until you get a clear(ish) link. With the gain right up, you will likely get feedback. Once you get feedback, you can back off the sensitivity on the receiver until you have a clear link.

To aid you in this task, it's a good idea to put something like a radio or smartphone playing music next to the microphone so you have a consistent sound to aim for.

If the above are all good and you still can't get sound from the receiver, switch the transmitter on and point the laser at a wall. Tap the front of the microphone repeatedly with your finger and watch the intensity of the laser spot. It should show brief and slight changes in intensity with each tap. If the variation is not apparent, check that the microphone is wired correctly.

If you have an oscilloscope, check the voltage from the electret microphone at the MIC input on the PCB and the base of Q3. The signal should be easily visible on the 100mV/div range. Look for a similar signal on the cathode of the laser; it should be much the same signal as you saw on the input. **PE**

Left: this photo shows how the battery, PCB, switch and speaker are mounted in the Receiver. The PCB is held to the rear of the lid by the potentiometer nut. An individual shot of the PCB is also shown.



Circuit Surgery

Regular clinic by Ian Bell

Topics in digital signal processing – sinc filters

We are looking at various topics related to digital signal processing (DSP).

DSP covers a wide range of electronics applications where signals are manipulated, analysed, generated, stored or displayed as digital data but originate from and/or are converted to real-world signals for interaction with humans or other parts of the physical world.

Fig.1 shows the key elements of a generic DSP system with a signal path from an analog input via digital processing to an analog output. This does not necessarily represent every DSP system (not all have all the parts shown), but it serves as a reference for the various subsystems we will consider.

Last month, we discussed the general structure of basic digital filters, which allows us implement a wide range of filters by using different sets of coefficients. This month, we will start to look at how those coefficients are calculated to achieve the desired filter.

Digital filter design

Last month, we also continued our discussion on implementing digital filters in LTspice The LTspice electronics simulation software package enables us to obtain transient and frequency response analyses based on the maths of a digital filter (we use LTspice behavioural sources to implement the filter maths).

However, additional circuitry, such as antialiasing and reconstruction filters, could be implemented using more realistic circuit models to help investigate overall system performance. The additional circuitry can be also be implemented in idealised behavioural form to investigate the general principles of DSP systems.

The example filter used over the last couple of articles was a moving average filter. This was chosen as an example because it is easy to understand the function it is performing and the calculations behind it.

Moving average filters are very effective at removing random noise from signals, particularly where the timing needs to be preserved as much as possible through the filtering process. However, they are not very useful for frequency separation, ie, rejecting one range of frequencies while passing another.

Sinc filters

There are many approaches to designing digital filters, so we will not provide comprehensive coverage of the types and techniques in this series. However, it is useful to go beyond the moving average filter and look at a slightly more complex, but still reasonably straightforward, approach called the 'windowed sinc' filter.

This type of filter can provide good frequency separation, but it is not as good as a moving average in terms of timing and pulse response behaviour. We will discuss the sinc aspect of the filter this month, and leave windowing for next month.

The term 'sinc' in the filter's name indicates the mathematical function used. We introduced the sinc function in the October 2024 *Circuit Surgery* column in the context of DAC frequency response.

$$\mathrm{sinc}(x) = \frac{\sin(x)}{x}$$

To recap, the sinc function is defined as:

When x is zero, we get 0/0, which is mathematically problematic (due to division by zero). However, for consistency and utility, sinc(0) is defined to be 1. A variant of this function is the normalised sinc function, denoted by a subscript π:

$$\mathrm{sinc}_{\pi}(x) = \frac{\sin(\pi x)}{\pi x}$$

This function occurs frequently in DSP and telecommunications. The importance of the sinc function comes from the relationship between the time and frequency domain representations of signals and frequency responses; in particular, in the contexts of ideal frequency responses and stepped signals.

Spectra

Converting a signal waveform (time domain) to its frequency domain representation gives us the spectrum of the signal – a plot of the frequency content. We have shown the theoretical signal spectra several times in this series on DSP, and have used LTspice to plot the spectra of simulated waveforms.

In the lab, many oscilloscopes and all spectrum analysers can display the spectra of real signals. Spectra provide useful information on signal quality, show the need for or effect of filtering, and help us understand phenomena such as aliasing.

As we have mentioned before, mathematically, a function in the time domain is converted to the frequency domain using the Fourier transformation. LTspice uses an algorithm called the Fast Fourier Transform (FFT) to calculate waveform spectra. We can also convert from the frequency domain to the time domain using the inverse Fourier transform.

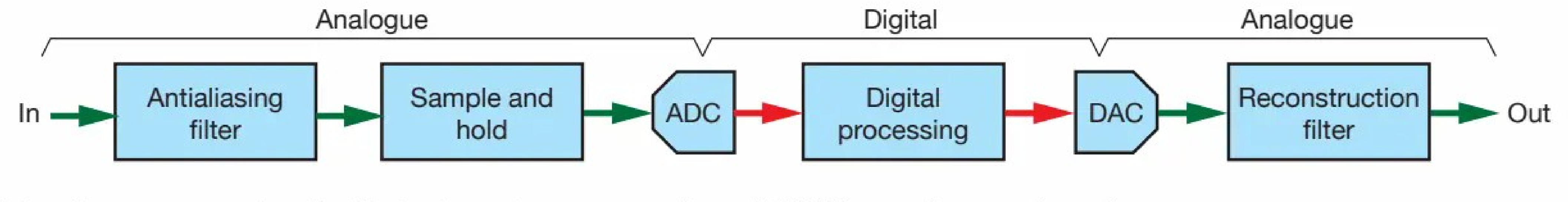


Fig.1: a generic digital signal processing (DSP) system structure.

Simulation files

Most months, LTSpice is used to support descriptions and analysis in Circuit Surgery.
The examples and files are available for download from the PE website:
https://bit.ly/pe-downloads

The mathematics are different for continuous and sampled signals. For sampled signals, the discrete Fourier transform (DFT) and its inverse are used (the FFT is an efficient implementation of the DFT).

Fortunately, for basic design and analysis, we do not have to perform detailed mathematics. It is either built into software tools or measurement instruments, or forms the basis of techniques which do not require heavy maths.

Impulse response

Converting from a frequency response (the gain of a circuit such as a filter or amplifier versus frequency) to the time domain may be less familiar than obtaining signal spectra. However, it is another important concept and the result is the impulse response of the circuit.

We introduced the idea of impulse responses last month. To recap, for continuous time systems, an impulse is an infinitely short pulse of unit area, but for sampled signal processing, it is a single sample of value 1.

The impulse response is the output produced when the input to a circuit is an impulse at time zero and the input is otherwise zero for all time.

We discussed the structure of basic digital filters last month. For the Finite Impulse Response (FIR) filter shown in Fig.2, the input and the input delayed by multiples of the sampling period are multiplied by the N coefficients a_0 to a_{N-1} and summed to obtain the output. We showed that with an impulse input, the filter will output the values of its coefficients in sequence.

To put it another way, the coefficients are equal to the impulse response of the filter, so if we know the impulse response of the desired filter we have the coefficient values required to implement it.

It follows that if we want to try to create an ideal filter, it helps to find the impulse response via the inverse Fourier transform of an ideal frequency response (brick wall filter).

The result for an ideal low-pass filter is that the impulse response is a sinc function. This is illustrated in Fig.3 for a continuous time filter. The upper plot shows the ideal frequency response for a low-pass filter with a bandwidth (cutoff frequency) of f_B and gain of one (unity gain) in the pass band. The impulse function of the filter (where t is time) is written as:

$$2f_B \operatorname{sinc}_\pi\left(2f_B t\right)$$

The frequency response plot in Fig.3 shows both positive and negative frequencies, as we have done before, and as is commonly the case when discussing signal processing theory. The impulse response time axis is scaled by $2f_B$, so the graph is generally applicable and clearly shows the integral zero-crossing points of the normalised sinc function.

Coefficients

Fig.3 and the sinc function above apply to continuous time functions. For DSP with sampled data, things are slightly different. The cutoff frequency f_c is expressed as a fraction of the sampling frequency f_s, so for a bandwidth as shown in Fig.3, we would use $f_c = f_B / f_s$.

Given that the Nyquist limit constrains signals to be below half the sampling frequency to prevent aliasing, f_c is in the range 0 to 0.5.

The sinc function for the impulse response above is continuous in time t, but for a digital filter, we have a discrete set of coefficients that we can refer to using an index k, which references the sample times (these occur at times kT where T is the sample period). For the digital sinc filter, the impulse response is given by:

$$2f_c \operatorname{sinc}_\pi\left(2f_c k\right)$$

In the ideal case, the index (k) ranges from negative infinity to positive infinity because the sinc function has non-zero values over an infinite range. In reality, of course, we cannot have an infinite number of coefficients. The simplest solution is to use a reduced range that is practical. This means that the filter response will be non-ideal.

As we will discuss in more detail next month, simply truncating the set of coefficients like this works, but does not produce the best filter response.

The sinc function is symmetrical about zero, so the total number of coefficients (N) should be odd to have the same number of coefficients either side of zero. Therefore, the index (k) ranges from $-(N-1)/2$ through zero to $+(N-1)/2$.

The positive part of the index range implies future values of the signal (current time is zero), so as discussed in December 2024 *Circuit Surgery*, such filters are referred to as non-causal and cannot be implemented.

The solution is straightforward: the coefficients are time shifted so that the $-(N-1)/2$ to $+(N-1)/2$ index range maps to 0 to $N-1$. For example, for 25 coefficients, the theoretical index range is –12 to +12, but in the practical implementation, the shifted coefficient index range (the i in a_i in Fig.2) is 0 to 24.

To calculate coefficients for the filter structure shown in Fig.3 with an index i in the range of 0 to $N-1$, we use $k = i - (N-1)/2$ as the index in the impulse response function above. This gives:

$$a_i = 2f_c \operatorname{sinc}_\pi\left(2f_c\left(i - \frac{N-1}{2}\right)\right)$$

The non-causal theoretical filter has zero delay, but the coefficient time-shift for the causal realisation results in a signal delay from input to output. This delay is equal to the coefficient shift, which is $(N-1)/2$. So, for example, a 25-coefficient filter will have a delay of 12 sample periods.

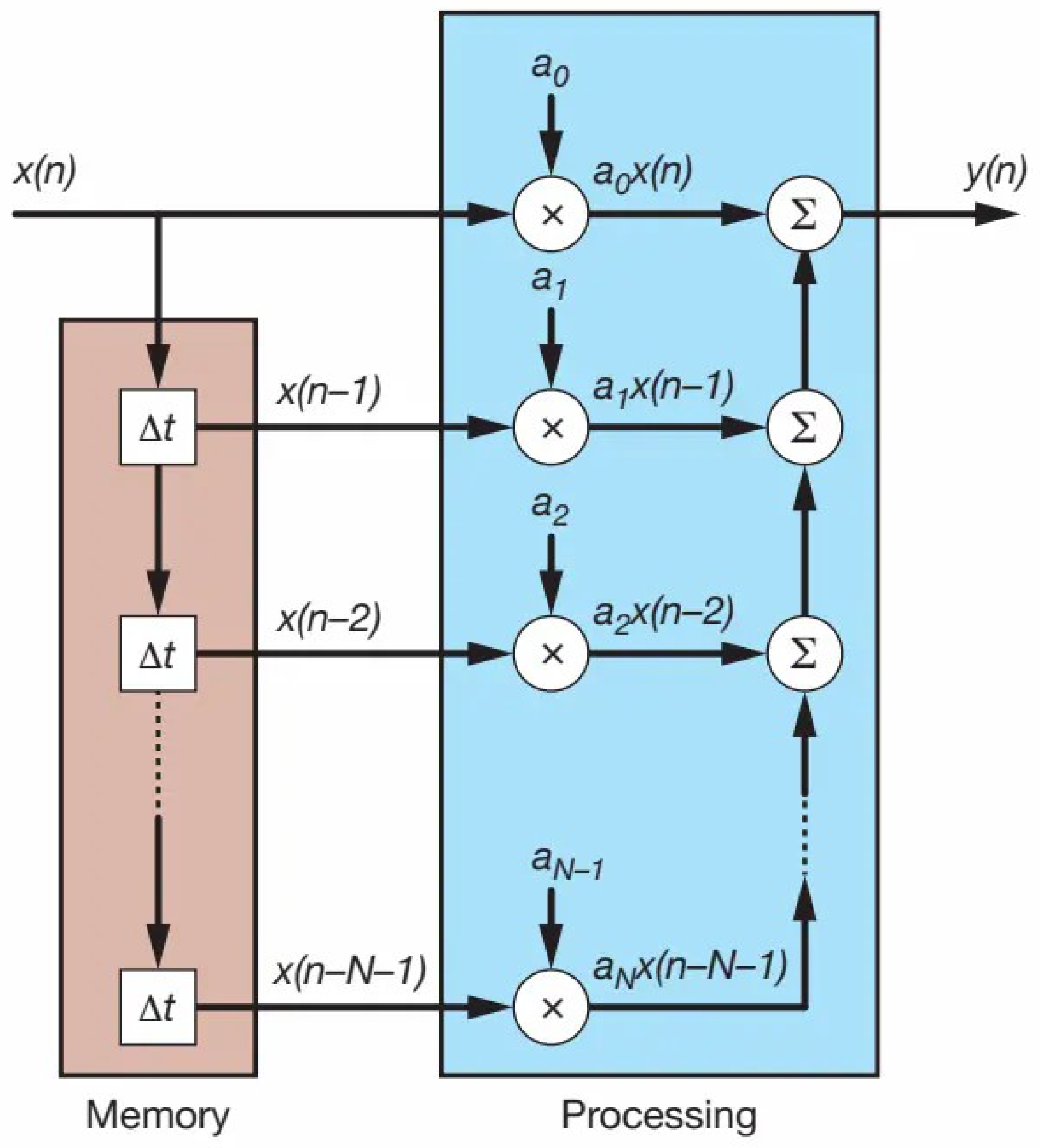


Fig.2: the structure of a finite impulse response (FIR) filter.

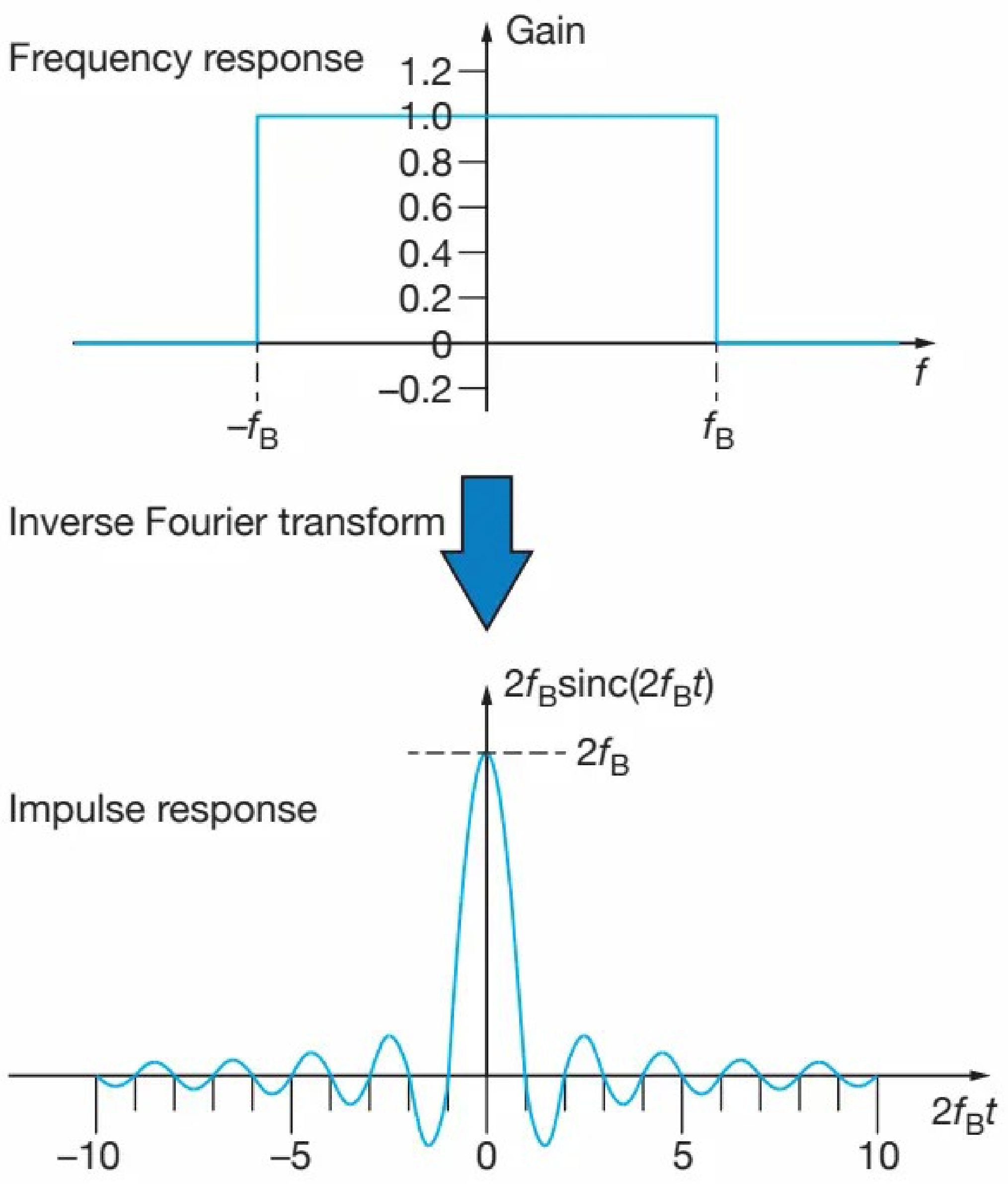


Fig.3: the impulse response of an ideal low-pass filter.

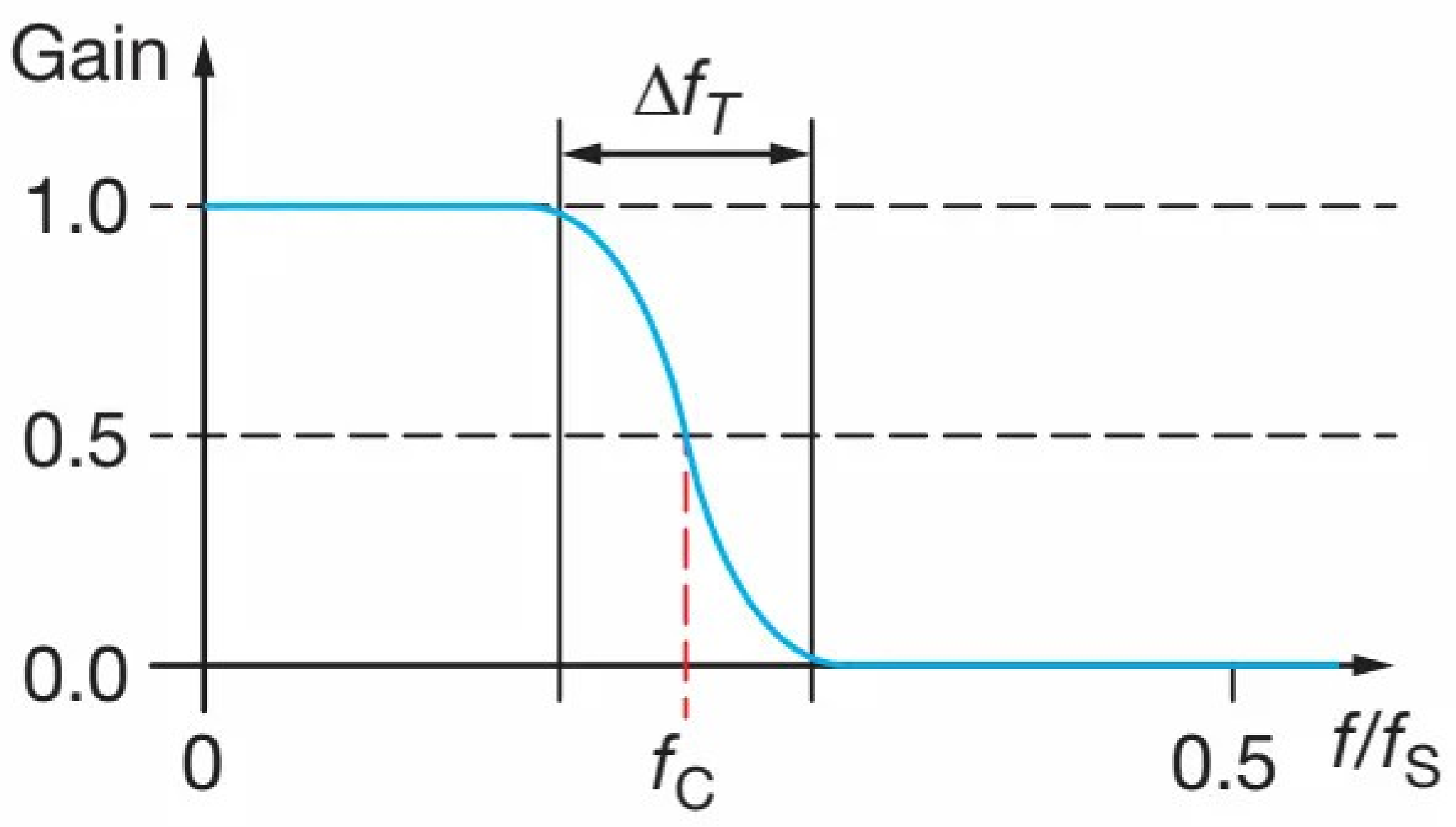


Fig.4: the cutoff frequency and transition bandwidth of a low-pass filter.

If it is necessary to combine or compare the filtered and non-filtered signals, the non-filtered signal will have to be delayed by the number of sample periods equal to the filter's delay.

Transition bandwidth

The number of coefficients determines how sharp the cutoff of the filter is; the more coefficients, the sharper the cutoff. This can be expressed numerically as the transition bandwidth (f_T) or roll-off. The transition bandwidth is the fraction of the sampling frequency (f_s) over which the filter gain changes from the pass band to the stop band.

Exactly where the transition band starts and ends is a somewhat arbitrary definition but could be, for example, from 99% to 1% of the gain in the pass band. Fig.4 shows an example where the transition bandwidth is about 0.1.

A commonly used approximation for the width of the transition band is 4 / *N* where there are *N* coefficients, but this applies to the improved (windowed) versions, which we have not discussed yet. Even then, it varies with the details of implementation. For simple truncation of the coefficients, as described above, the transition bandwidth is better estimated using 0.9 / *N*.

The filter coefficients (a_i) can be calculated as described above. Before doing this, the number of coefficients has to be decided. This could be simply a decision based on what is considered achievable. Alternatively, the desired transition bandwidth could be used to calculate the number of coefficients required – assuming the relationship such as $f_T = 0.9 / N$ is known for the filter being designed.

And as can be seen from the reciprocal relationship to *N*, sharper cutoffs require more coefficients. If the filter is implemented in digital hardware, this implies a larger circuit.

For software implementations, more calculations are required, which requires more time and therefore reduces the maximum sampling rate which can be used. After all, the calculation process has to be completed within each sampling period for the filter to keep up with the incoming signal data.

Increasing the number of coefficients also increases the delay of the signal through the filter.

One disadvantage of sinc filters is that they are relatively inefficient in terms of processing time. However, faster approaches tend to be more complex and difficult to work with.

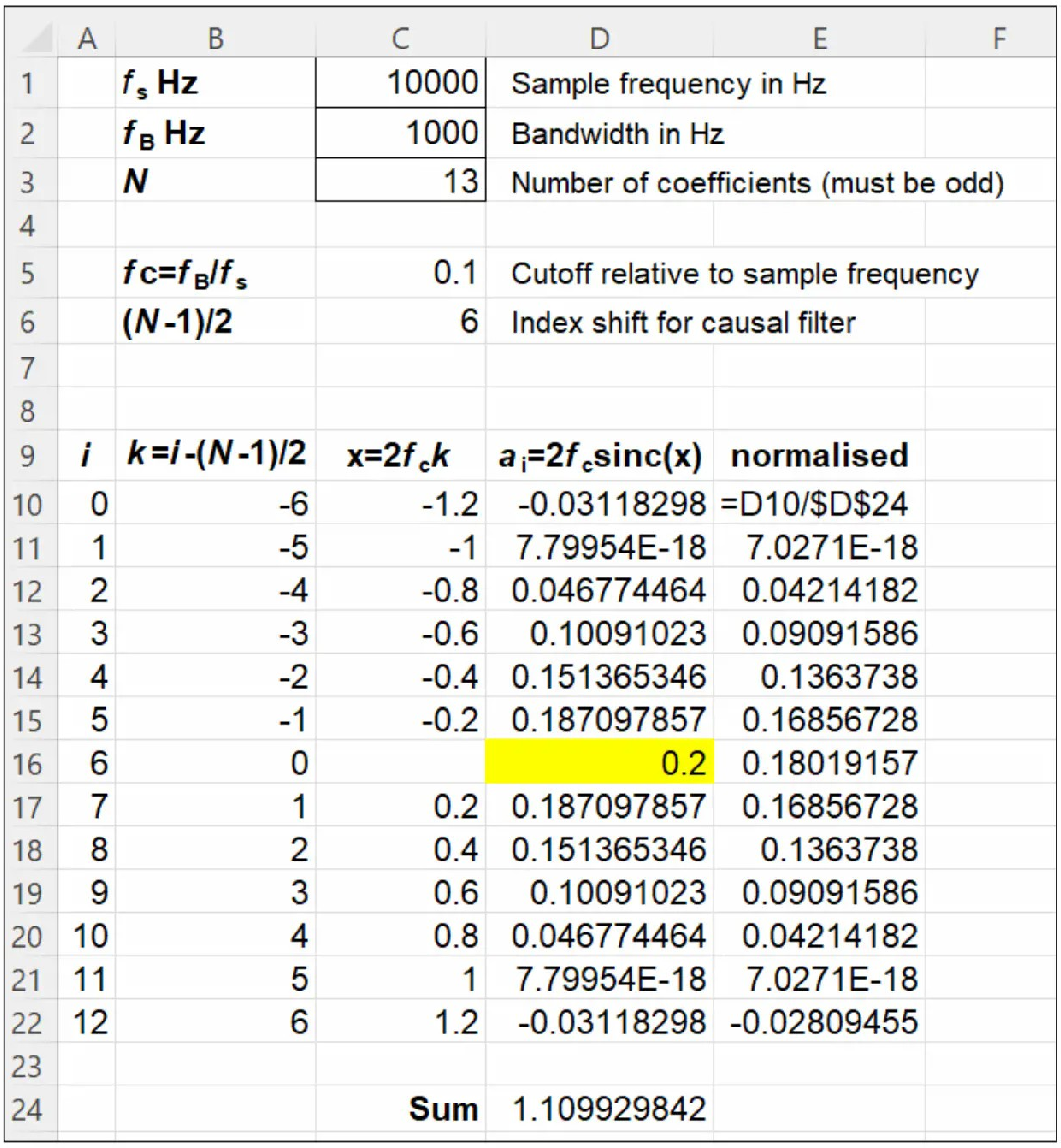
Calculating the coefficients

If we apply a constant value of 1 to a low-pass sinc filter, the output will settle to a value equal to the sum of all the coefficients. This should be clear from Fig.2 – if the input and all the stored samples are 1, the output is equal to the sum of all the coefficients multiplied by 1, that is the sum of the coefficients. This is the filter's gain at DC or very low frequencies, well into the pass band.

If a filter of unity gain is required, the coefficients obtained from the impulse response can be normalised by dividing each of the values by the sum of the coefficients.

Although there are software tools and online calculators to find digital filter coefficients, it is instructive to perform some of these calculations to see how things work, so we will go through an example here. Filter coefficients can be calculated manually, but it is more efficient to use a spreadsheet such as Microsoft Excel and LibreOffice Calc.

Alternatively, if you can write code (for example in C or Python), it only takes a few lines to perform the calculations to find low-pass sinc filter coefficients.



	A	B	C	D	E	F
1		**f_s Hz**	10000	Sample frequency in Hz		
2		**f_B Hz**	1000	Bandwidth in Hz		
3		**N**	13	Number of coefficients (must be odd)		
4						
5		**$fc=f_B/f_s$**	0.1	Cutoff relative to sample frequency		
6		**$(N-1)/2$**	6	Index shift for causal filter		
7						
8						
9	**i**	**$k=i-(N-1)/2$**	**$x=2f_ck$**	**$a_i=2f_c\text{sinc}(x)$**	**normalised**	
10	0	-6	-1.2	-0.03118298	=D10/$D$24	
11	1	-5	-1	7.79954E-18	7.0271E-18	
12	2	-4	-0.8	0.046774464	0.04214182	
13	3	-3	-0.6	0.10091023	0.09091586	
14	4	-2	-0.4	0.151365346	0.1363738	
15	5	-1	-0.2	0.187097857	0.16856728	
16	6	0		0.2	0.18019157	
17	7	1	0.2	0.187097857	0.16856728	
18	8	2	0.4	0.151365346	0.1363738	
19	9	3	0.6	0.10091023	0.09091586	
20	10	4	0.8	0.046774464	0.04214182	
21	11	5	1	7.79954E-18	7.0271E-18	
22	12	6	1.2	-0.03118298	-0.02809455	
23						
24			**Sum**	1.109929842		

Fig.5: this spreadsheet can calculate the coefficients for a sinc low-pass filter.

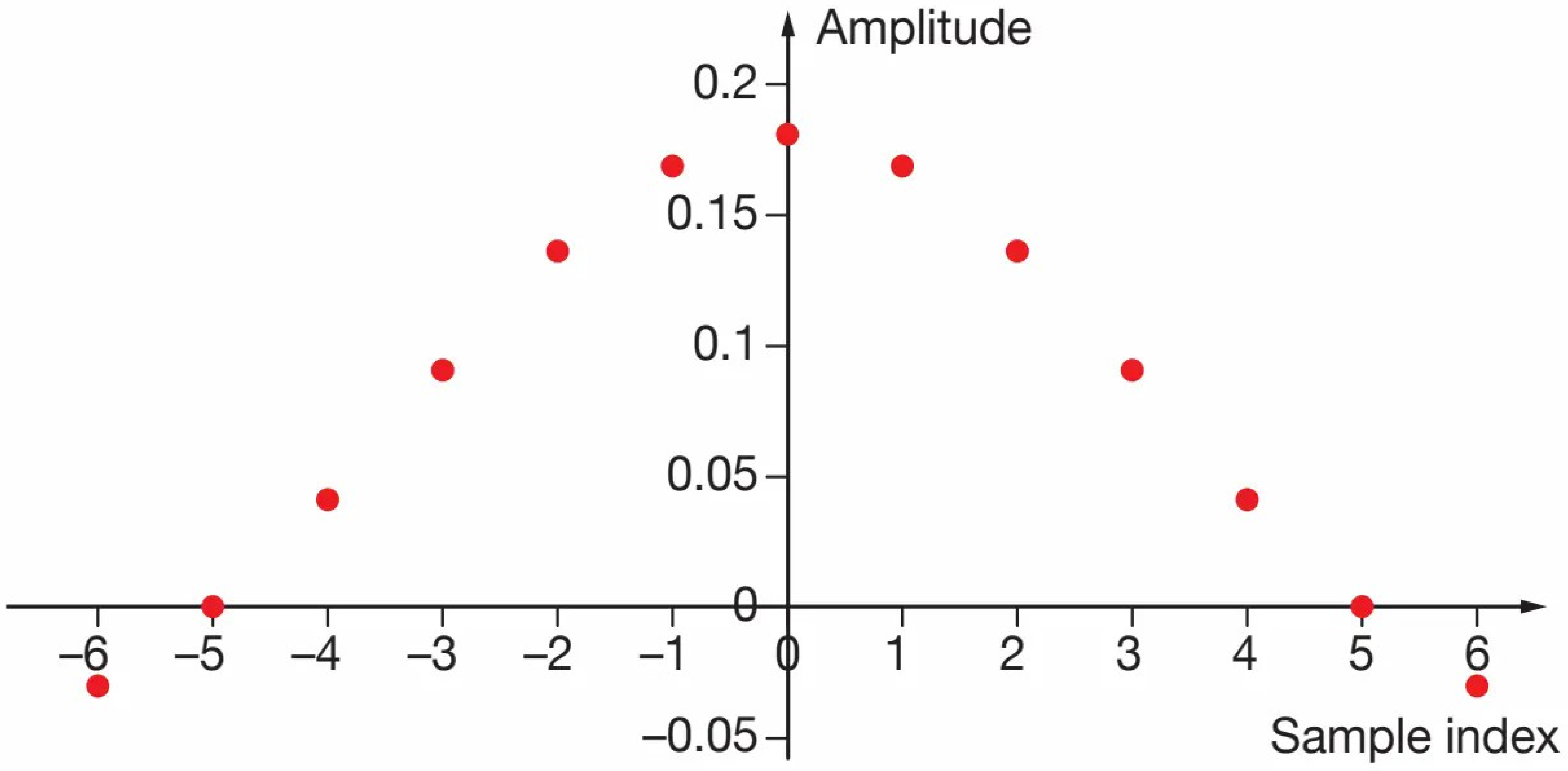


Fig.6: the impulse response of the filter obtained from the spreadsheet in Fig.5.

The spreadsheet shown in Fig.5 calculates the low-pass sinc filter coefficients from the sampling frequency (f_s), required bandwidth (f_B) and number of coefficients (*N*) using the equation for a_i given above. *N* must be odd. These values are entered on the first three rows.

In row 5, the cutoff relative to the sample frequency is calculated as $f_c = f_B / f_s$ using the formula **`=C2/C1`**. This value occurs in the functions used to calculate the coefficients and is referenced using **`$C$5`**.

For readers not very familiar with spreadsheets, if the content of a cell (box in the grid) starts with an equals sign (**`=`**), it is interpreted as a formula and the spreadsheet performs the given calculation. The formulae can use basic arithmetic and built-in maths operations (such as **`SIN()`** for sine).

The values of cells are referred to by their row and column coordinates. For example, the value of 10000 for f_s in the example is obtained using **`C1`**.

It is common for the same formula to be used on many rows, using data that varies down a column (or vice versa). Therefore, Excel automatic adjusts the cell references when performing copy and paste operations on formulae. This makes it easy to create many rows of similar calculation by pasting.

This goes wrong where a constant value is required in all the functions over multiple rows (eg, f_c is used in all the coefficient calculations). To use a constant cell reference, a **`$`** character is included in cell coordinate, eg, **`$C$5`** rather than **`C5`** for the cell containing f_c.

In row 6, the index shift is calculated as $(N - 1) / 2$ using the formula **`=(C3-1)/2`**. This value is used to find the index value *k* to use in the coefficient calculation from the index *i* used in the filter. It is referred to using **`$C$6`**. In this example, we use a low value of 13 for *N* to keep the spreadsheet small.

The values of *i* can be seen ranging from 0 to 12 ($N - 1$) in column A in rows 10 to 22. The value of *i* in rows 11 to 22 is found by adding one to the value in the previous row. For example, cell A11 has the formula **`=A10+1`**.

Columns B to D break the coefficient calculation into steps. This is not strictly necessary, but makes the spreadsheet formulae easier to work with, as large formulae can be difficult to read. Column B is used to calculate the index *k* from index *i* using the index shift value from cell **`C6`**. For example, in row 10, the formula is **`=A10-$C$6`**.

Column C is used to calculate the value that is going into the sinc function (x) as $x = 2f_ck$ using the formula (again in row 10) **`=2*$C$5*B10`**. In column D, the coefficient a_i is calculated as $2f_c.\text{sinc}_\pi(x)$ using the formula (in row 10):

```
=2*$C$5*(SIN(PI()*C10)/(PI()*C10))
```

The function **`PI()`** evaluates to the value of π.

This formula is not applicable when $x = 0$, which occurs when *i* is in the middle of its range (6 in the example). Here, the value of the sinc function is set to 1, so the spreadsheet formula is different in that row. In this case, cell D16 has the formula **`=2*$C$5*1`** to calculate $2f_c \times 1$. The 1 is included as a reminder of sinc(0) being used, and the cell is highlighted.

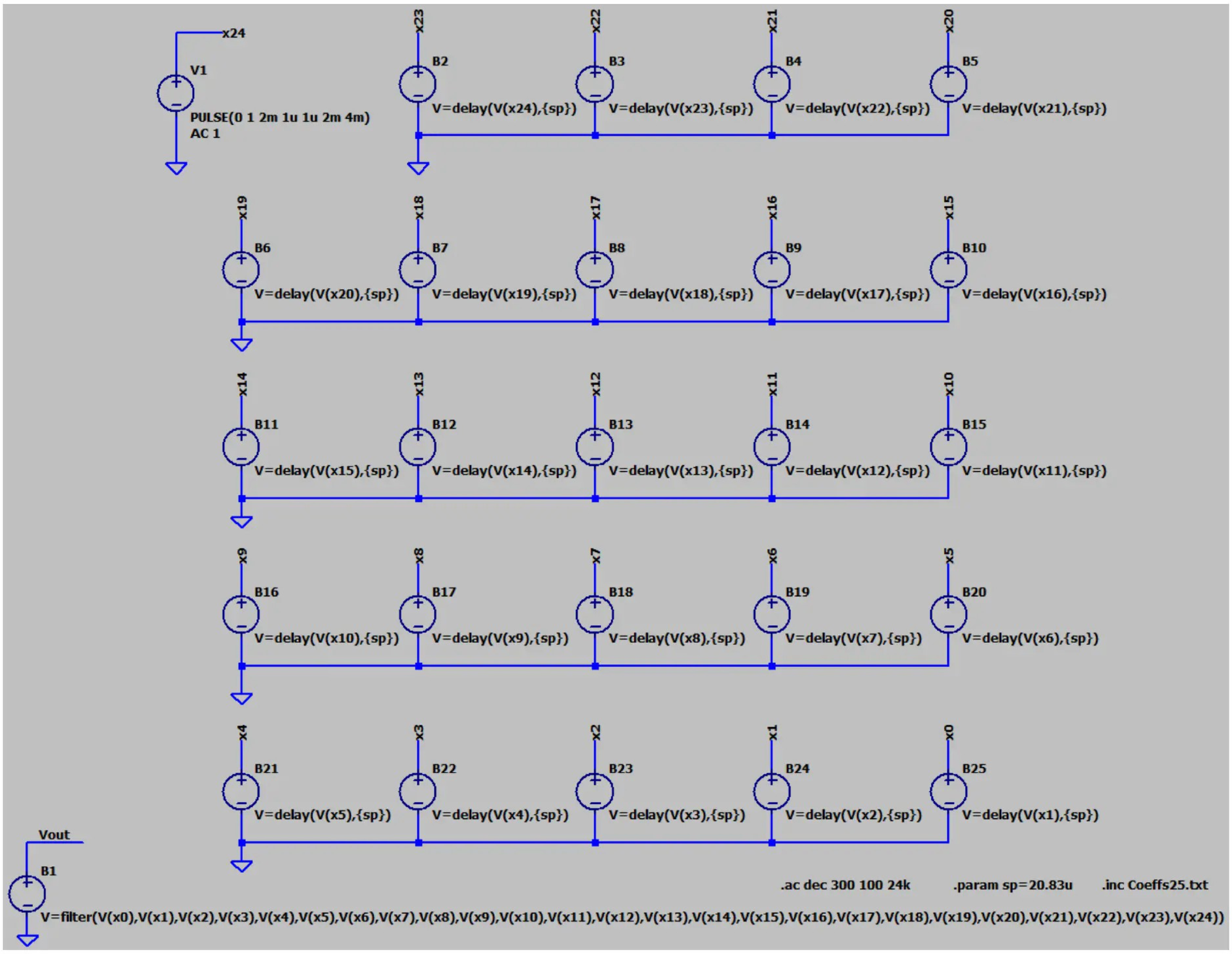

x24
V1
PULSE(0 1 2m 1u 1u 2m 4m)
AC 1
x23
B2
V=delay(V(x24),{sp})
x22
B3
V=delay(V(x23),{sp})
x21
B4
V=delay(V(x22),{sp})
x20
B5
V=delay(V(x21),{sp})
x19
B6
V=delay(V(x20),{sp})
x18
B7
V=delay(V(x19),{sp})
x17
B8
V=delay(V(x18),{sp})
x16
B9
V=delay(V(x17),{sp})
x15
B10
V=delay(V(x16),{sp})
x14
B11
V=delay(V(x15),{sp})
x13
B12
V=delay(V(x14),{sp})
x12
B13
V=delay(V(x13),{sp})
x11
B14
V=delay(V(x12),{sp})
x10
B15
V=delay(V(x11),{sp})
x9
B16
V=delay(V(x10),{sp})
x8
B17
V=delay(V(x9),{sp})
x7
B18
V=delay(V(x8),{sp})
x6
B19
V=delay(V(x7),{sp})
x5
B20
V=delay(V(x6),{sp})
x4
B21
V=delay(V(x5),{sp})
x3
B22
V=delay(V(x4),{sp})
x2
B23
V=delay(V(x3),{sp})
x1
B24
V=delay(V(x2),{sp})
x0
B25
V=delay(V(x1),{sp})
Vout
B1
.ac dec 300 100 24k
.param sp=20.83u
.inc Coeffs25.txt
V=filter(V(x0),V(x1),V(x2),V(x3),V(x4),V(x5),V(x6),V(x7),V(x8),V(x9),V(x10),V(x11),V(x12),V(x13),V(x14),V(x15),V(x16),V(x17),V(x18),V(x19),V(x20),V(x21),V(x22),V(x23),V(x24))

Fig.7: an LTspice schematic implementing a low-pass sinc filter.

Spreadsheet cell D24 uses the formula **`=SUM(D10:D22)`** to calculate the sum of all the coefficients. In column E, the value of each coefficient from column D is divided by the sum value using (for row 10) **`=D10/$D$24`**. This produces the set of normalised coefficients, resulting in a filter with a gain of 1 in the pass band.

Fig.6 shows the impulse response of the filter obtained from the spreadsheet in Fig.5. This is a plot of the normalised coefficient values against sample index *k*.

Simulation example

The LTspice schematic in Fig.7 implements the digital filter calculations for a 25-coefficient, 1kHz low-pass sinc filter with a sampling rate of 48kHz (a 20.83µs sample period). This schematic is just the digital filter part, but uses the same approach as previous examples.

If required, sampling, antialiasing, reconstruction filters and other system or analysis components can be added in line with previous discussions.

As explained last month, we have placed the coefficients and filter calculation function in an include file, rather than directly on the schematic. This code is shown in Fig.8.

The reason we do this is to make it easier to see and edit the coefficients and to avoid cluttering the schematic up with too much extraneous text.

The coefficients used here were calculated using a spreadsheet similar to the example discussed above. The results from simulating the filter are shown in Fig.9. You will find similar plots in many DSP chip data sheets as such digital filters are widely used.

```
.func a(i) {table(i,
+ 0,0.02951210551,
+ 1,0.03191959113,
+ 2,0.03420780599,
+ 3,0.03635417297,
+ 4,0.03833734989,
+ 5,0.04013747349,
+ 6,0.04173642024,
+ 7,0.04311799631,
+ 8,0.04426815733,
+ 9,0.04517517611,
+ 10,0.04582976922,
+ 11,0.04622523114,
+ 12,0.04635750502,
+ 13,0.04622523114,
+ 14,0.04582976922,
+ 15,0.04517517611,
+ 16,0.04426815733,
+ 17,0.04311799631,
+ 18,0.04173642024,
+ 19,0.04013747349,
+ 20,0.03833734989,
+ 21,0.03635417297,
+ 22,0.03420780599,
+ 23,0.03191959113,
+ 24,0.02951210551)}

.func filter(x0,x1,x2,x3,x4,x5,x6,x7,x8,x9,x10,x11,x12,
+ x13,x14,x15,x16,x17,x18,x19,x20,x21,x22,x23,x24) {
+ a(0)*x24+a(1)*x23+a(2)*x22+a(3)*x21+a(4)*x20+
+ a(5)*x19+a(6)*x18+a(7)*x17+a(8)*x16+a(9)*x15+
+ a(10)*x14+a(11)*x13+a(12)*x12+a(13)*x11+a(14)*x10+
+ a(15)*x9+a(16)*x8+a(17)*x7+a(18)*x6+a(19)*x5+
+ a(20)*x4+a(21)*x3+a(22)*x2+a(23)*x1+a(24)*x0}
```

Fig.8: the code in the include file (Coeffs25.txt) used in the LTspice schematic in Fig.6.

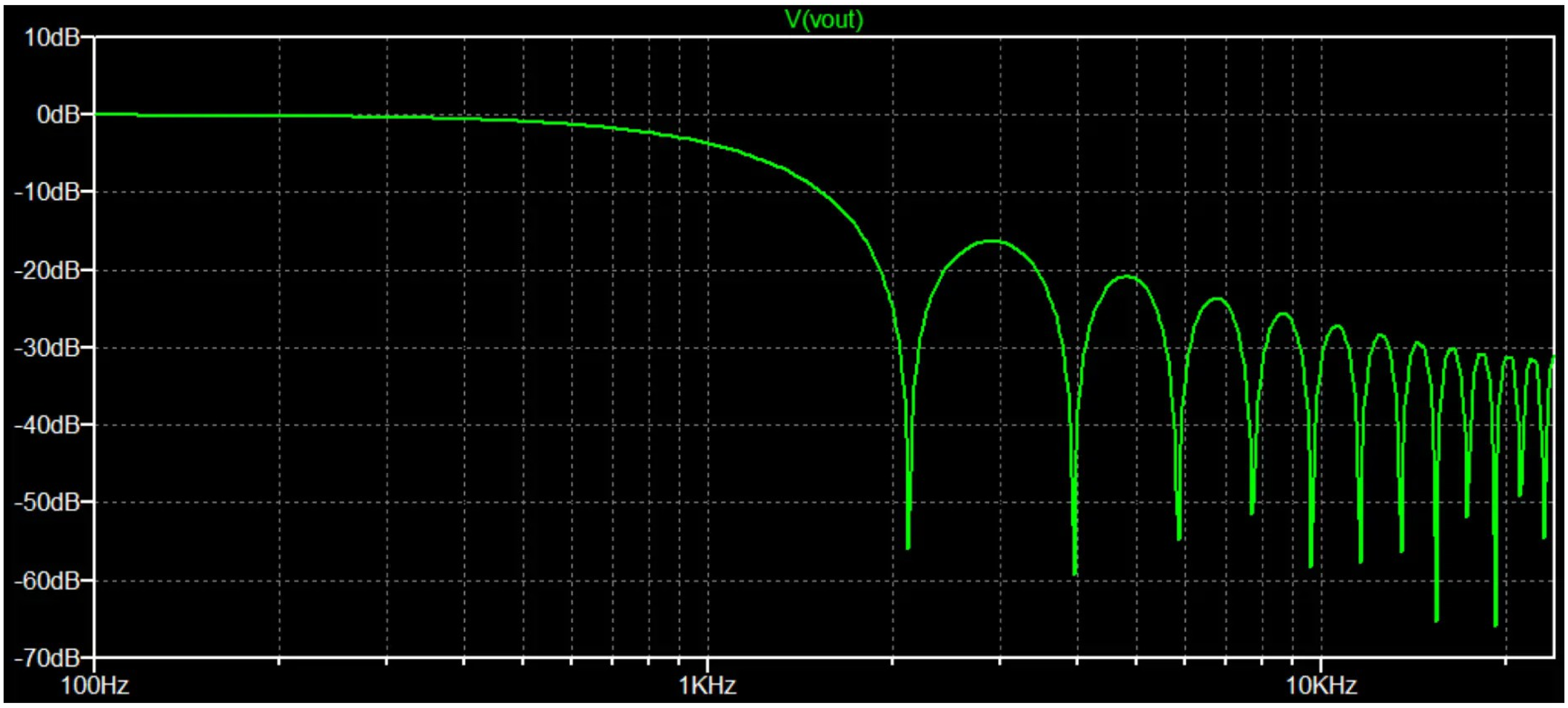


Fig.9: the simulated frequency response of the filter in Fig.6.

The **Fox** Report

Barry Fox's technology column

Hi-Fi making a comeback & new EU digital tagging law

Since COVID-19 and the maturing of Zoom, companies have taken the cheap and easy way out of staging industry conferences. Instead of hiring a hall, providing refreshments and booking speakers with something worth hearing to say, they have often let self-promoting managers pre-record a speech someone else has written and duck questions.

So, hats off to the bodies like electronics industry market analysts Futuresource (www.futuresource-consulting.com) that still put on real live being-there conferences, with meaty content and time for Q&A and old-fashioned personal networking. The DTG, the UK's Digital Technology Group (https://dtg.org.uk/), is another body that still does real conferencing.

At the recent Futuresource Audio Collaborative annual event at London's Soho Hotel, a string of speakers applauded Apple's recent commitment to combine headphone and earbud music listening with hearing aid technology. It's a logical step that will remove the stigma of wearing ugly hearing aids by replacing them with stylish over-the-ear headphones or in-ear buds.

A smartphone or tablet will measure the owner's hearing and use AI to tweak the audio output to compensate for the deficiencies detected. AI will also handle the tricky task of separating live conversation from background noise and music.

The ongoing development of low power-drain chips for the new Bluetooth Low Energy standard and the coming of higher capacity batteries will make running times between charging more realistic.

This gels with the audio trade statistics distilled by Futuresource research analyst Kavish Patel. Headphone listening remains one of the few consistent areas of growth, with 'old-fashioned' over-the-ear headphones making a comeback.

That includes True Wireless Stereo (which needs no wire between left and right earpieces) and UWB Ultra-Wideband wireless links, which use pulse coding at higher frequencies than Bluetooth or Wi-Fi for precise location tracking.

"When people try listening to better quality sound, they then know they want it", said Kavish Patel. Several speakers then warned that the industry's big challenge now is to show consumers why it is worth spending $400 on a pair of buds or cans, when what looks like the same thing can be bought for $15.

"How do you tell your story in three seconds and a listing on Amazon? Education for consumers needs to be better", became a familiar cry throughout the event.

No-one could say how the education should be done. Magazines like this are read by tech enthusiasts, not mass-market customers interested in trendy gadgetry. Trendies get their technical advice from online 'influencers', who have no clue how anything works, or from shop-floor staff who are often just as badly informed.

Industry trade body RETRA (the Radio, Electrical and Television Retailers Association) has now been absorbed by BIRA (the British Independent Retailers Association). BIRA has just now killed off the magazine called *Alert*, which kept dealers informed and better able to explain the difference between $15 and $400 earbuds.

A new immersive sound system called Amphi Multichannel Hi-D from a company called Audioscenic was promoted but not demonstrated. Amphi builds on previous attempts at getting a binaural headphone surround sound image from loudspeakers.

The basic technique (as used decades ago by JVC for a long-forgotten system called Bi-Phonics) remains the same: they doctor the phase and level of different frequency bands from the left and right speakers so that the listener's right ear does not hear the left sound and vice versa.

Now, as then, the system needs to know the listener's position. This is relatively easy if the listener is sitting at a PC, at a conference table, in a fixed car seat, or even a dentist's chair. AI will help, but even the cleverest system will not have much success at location tailoring if several people are lolling on a living room sofa or in different chairs and not sitting still.

Past systems have failed commercially because most people find it easier and more relaxing just to continue listening to old-fashioned stereo from a pair of speakers working on the principles laid down in the 1930s by British electronics pioneer Alan Blumlein.

Lisa Stafford, from a company called TAZAAR, was billed to speak about 'sustainability', which is usually a sure-fire yawn-maker. But she jolted the audience into interest when describing the new "Digital Product Passport".

It emerged that in 2024 the EU passed laws which, from 2026, will require all

Maintaining Brand Relevance in a Digital World
#AudioCollab2024
Guy Hammett
Senior Market Analyst, Home Audio - Futuresource Consulting
Sarah Yule
Marketing Director EU & General Manager - KEF Music Gallery London
Andy Dowell
Director of Business Development - MQA Labs & Lenbrook Media Group
Scott Campbell
Director of Sales - HARMAN
Julien Bergere
Chief Commercial Officer - Dynaudio

electronics (along with textiles and booze) to be digitally tagged – eg, with a QR code – which holds product information and a log of the product's history.

Once Ms Stafford had moved on from somewhat vague talk about using the new passport to "set up meetings, influence positive actions, create communities of owners, build customer loyalties, foster a cheaper way to spread word of mouth and reduce landfill", some hard facts started to emerge.

So far, digital device passports have been used only for luxury goods, like top-end cars and watches, and in the automotive and aerospace industries, as an alternative to paper records for countering the sale of counterfeit spares. But, in theory at least, the time is coming when shirts, hats and socks will be coded.

Ms Stafford predicts that within the next five years, the effect will be huge. Batches of just about anything will be traceable. Owners will be alerted to problems. How? Mobile apps will be involved. Even wine bottles will be tagged.

This raises all manner of knock-on issues. Will alerts end up in spam traps? How will people who do not have a smartphone be warned about a problem with their socks? Will garments buzz or beep?

Badly handled, Digital Product Passporting could end up another well-intentioned but inadequately-thought-through 'official' idea that will create yet more red tape and paperwork for already struggling businesses – not just inside the EU, but anywhere in the world that is trading with the EU.

During the conference networking coffee break, an awful lot of people were saying the same thing: "It's completely new to me".

One of the last sessions of the day was for me the most provocative. The topic was connectivity, and a panel of experts debated in detail the pros and cons of all the new and coming wireless link technologies, including Bluetooth, Wi-Fi and UWB.

"Bluetooth is cheap and all devices are compatible", argued Maurice Moroney of Qualcomm. "Bluetooth does a bit of everything and is the de facto standard. The consumer wants not to care; not to care about how it works, just know that it works".

Alexander Tschekalinskij of the Fraunhofer research institute in Germany (creators of the MP3 standard) revealed the welcome news that "Fraunhofer is looking for one codec that does everything".

Jez Stark of UK research company Cambridge Consultants said, "Wire sets the benchmark. It's the lowest common denominator". Maurice Moroney put it another way: "Wireless is the invisible wire that the consumer can't see". So I put a question to the panel:

Why not use wire instead of wireless? With wire – or optic fibre – you get instant connection, with no need for pairing, no gobbledegook passwords, no struggling to set up Wi-Fi Mesh Extenders, no latency, no quality loss, no need for compression codecs, no inexplicable dropouts and disconnections, and no need to re-charge batteries for wire-free speakers or headsets?

With wire or fibre, there are virtually no security risks. Just plug in and switch on. Why is it so desirable to stop providing headphone jacks? Why create the situation where wirelessly connecting to one device can stop another device working, with reboots then needed to reconnect? In short, what has the industry got against wires?

Maurice Moroney of Qualcomm defended the quest for wire-free connection with curious logic: "With so many 'sinks and sources' (input, output, source, play and display devices) from so many different manufacturers, Bluetooth will never be completely right. But I was on the committee that designed the HDMI standards. That was wire, and it was a real nightmare."

Indeed, HDMI was and remains a pain in the neck. Connections often don't work or stop working until devices have been unplugged, re-plugged or re-booted. Ask any conference speaker who has tried to connect their laptop PowerPoint to a big screen or projector.

But that is not because HDMI uses a hard copper wire connection; it's because of all the complexity that is built into the HDMI standard, to make the copper connection rely on handshakes that are intended to block unauthorised copying and all too often also block legitimate connections.

"The driver of change is shareholder interest", reminded Moroney.

I was so gobsmacked by such an honest appraisal of why so much of the technology we now rely on behaves all year round like a dysfunctional family at Christmas that I asked Mr. Moroney to confirm what he had said as I wrote it down.

Put another way, "the driver of change is shareholder interest" means that manufacturers' drive for profit brings consumers misery. **PE**

HAMMOND®
1551W IP68 miniature enclosures
Learn more: hammondmfg.com/1551w
uksales@hammondmfg.com
01256 812812

Practically Speaking

Stories about real engineering – by Jake Rothman

Audio doubt and workshop woes

I said I wouldn't do it, but here we are. I'm writing a column about not being able to write my column. If those who write for *The Times* do it, why can't I?

It has all come to this because I have no electronics lab and am utterly bereft. I'm all packed up ready to move to Craven Arms, a railway junction town (named after a pub that's since closed) in the middle of nowhere, or Shropshire, if you've ever heard of it. However, I'm now in limbo because the buyers have gone cold, like my iron and scope.

The library is also packed: 22 boxes of A4 ring-binders weighing 12kg each in the hall. 90% of the information in them is not online and never will be since no one is going to scan it. I could just pull stuff off the 'net and make an article out of that, but we all know that's a con. Anyone could do that.

The rest of the workshop, weighing in at around three tonnes, is in the garage. I just hope the concrete floor doesn't give way! It used to hold a four-by-four, so I might get away with it. So all that's left for now are some old memories; I hope none are libellous.

Tele-phoney

One of my first weekend jobs, around 1982, was at a film broadcast equipment supply company in the West End of London. I mainly made leads and did repairs and servicing. As usual, things came in completely trashed. I had a pair of Beyer DT48 headphones that had been run over by a forklift truck and were completely mangled. "A few tweaks should do it," the customer said.

I ended up making an entirely new pair from spare parts and old headphones. I think the bill cost £5 less than a new pair at £150. They came in a few weeks later trashed again, covered in sticky latex rubber solution holding clumps of somebody's hair.

The top-notch mixing desks we supplied used to have Penny and Giles conductive plastic faders. In those days, it was normal to replace individual parts such as wipers, bushes and tracks. One unit from the sports room came back a few times with oddly pitted tracks and wipers that had gone green. There was also white powder in the bottom tray, which I dumped in the bin.

I told a senior technical guy about this, and he seemed strangely upset about the missing powder! Oh, the naivety of youth.

Sticky situations

Here's one to remind you of how one musician can destroy a company employing several good electronic engineers, so beware if you are designing for the non-technical.

It was early 1986 in Camden Town. I was a test engineer at a company making a leading-edge guitar synthesiser that could be played like a real guitar. Making one had always been the ambition of the decent CEO.

It had a MIDI output that controlled a lovely polyphonic analog synthesiser built around Solid State Music (SSM) chips. They were a significant improvement of the Curtis chips that were popular at the time.

All the circuit boards were top-notch surface-mount assemblies built by an avionics supplier in Reading. Even the guitar neck enclosed a long SMT board with LEDs denoting the positions of the frets.

The frets were called SCI, or semi-conductive intelligent. This was basically a cermet* pot track with a signal across it so that a particular string and its position could be sensed to allow for pitch bending. The six strings were also scanned to sense which ones were depressed.

Another clever trick was to separate the strings in the bridge position for strumming and picking, which made it easier to play than a normal guitar. I've always believed the best interface between man and electronics is the analog potentiometer, so the cermet frets seemed the right way to go, and they played beautifully to us engineers in the lab and the studio.

That was, until – you've guessed it – musicians started playing it live on stage. They pressed so hard that the ceramic frets cracked, and some even fell off! I remember frantic weeks trying to solder on new frets and trying to get them to the exact height the musicians expected.

I remember being scowled at by Kate Bush's technician, while never even getting a chance to see her as she looked around the company. Worse was to come, as the guitars then did crazy solos on stage all by themselves, making even Steve Vai seem slow. This was a result of random triggering as sweat rolled down the misaligned fretboard.

None of us in the lab realised that musicians sweated so much when they got into a frenzy. After all, we never did while looking at our scope traces and clean, dry circuits.

It was such an innovative piece of technology that it won a British Design Award for industry, with our CEO being presented with a trophy by the Duke Of Edinburgh. On his return, he wound the company up. It's a sad story, with around a million pounds burnt. I left with a Weller soldering iron and a few tubes of SSM 2024 filter chips.

Ghosts in the machine

Many musicians are superstitious, and some recording studios were built in Victorian, supposedly "haunted" buildings. As bored studio maintenance engineers in the days of tape, we used to play nasty tricks on some paranoid clients. One we used to like doing was laying down a half-hour track while they popped out for a few minutes.

We did it at very high tape speed, using sources that would spook the ghost-fearing client when played slowly at the correct speed. One ended up being mixed in, but I felt it would be cheeky to ask for a royalty.

---

* cermet refers to a ceramic strip glazed with a glass, metal and frit mixture, giving a stable and hard-wearing resistive element.

Another dodge was directed against arrogant old producers who claimed to have the hearing of a 20-year-old. We would mix in a 13kHz tone, which they couldn't hear. Old producers use spectrum analysers now, so they would see through this.

I even installed a big calibrated knob labelled FHS (Faux Harmonic Synaesthesia) in a mixer that did nothing, but some clients were convinced that it sounded better when set to a precise position!

Strange solutions

There was intractable hum in one Islington studio, I checked every Earth connection, cable shield, everything; no luck. After several coffee breaks, I gave up; nothing was making sense.

For inspiration, I went exploring, going into the basement to look at the reverb chamber and tape archive. In the dry, dusty basement, I noticed an odd thick-gauge Earth wire going into the corner. Kicking the dust away revealed an Earthing rod where the ground was completely dry.

I was suddenly overwhelmed with a desire to urinate, and reckoned I wouldn't make it back upstairs, so there was the possibility to solve two problems at once. For low hum, it is essential that the main ground reference at the mixing desk has a low im-pee-dance.

I never told them what I had done; I just issued an invoice for a day's diagnostics and a big bag of copper sulphate crystals. I recommended that they water the rod with copper sulphate solution every few months.

Silly puffs and fluff

I had one mixing engineer who always seemed to destroy the monitor speakers with too much bass, tearing the cones from their lead-out wires. I came up with the idea of putting a small pile of talcum powder at the back of the reflex ports. If he overdid it, puffs of white "smoke" would appear and warn him of an additional invoice. I got found out when I inadvertently used perfumed talc.

In 1989, I moved into lecturing where the main hazards were political rather than electrical, but loads of funny things kept happening.

One of the first classes I taught was "Electronics for Guitars", where the ambient IQ was rather low. I said to a student that he could check if his 9V PP3 batteries for the pedals were okay by just touching the terminals on his tongue.

The next day, I was having a nice cup of tea in the canteen and I heard a funny sounding "yelp". It was the student, jumping about with an unusual-looking battery stuck to his tongue. We later found out it was one of the new lithium batteries that had just come out for smoke alarms. These had much greater current capability than the old zinc-carbon types!

Fluffy bunnies

Most furry objects found in sound engineering are microphone windshields. However, we used to pretend there were also extra uninvited guests. Small speakers under floors and in walls were always a good Halloween trick. A few speakers fed with a bit of judicious microphone scratching switched around would send some into a frenzy.

I worked with one prissy lecturer who was terrified of rodents, so we built a hidden pulse-generator driving a little "squeak" tone burst into a piezo disc. The beep was so short and infrequent that the matchbox-sized unit was never found.

Near misses

When teaching practical electronics, there was always a risk of accidents. Any incidents had to be written up in an accident report book. Occasionally, some students did things that were unbelievable.

I had one guy from Bolton who used to hold solder in his mouth, saying it gave him an "extra hand". I gave him some advice about lead poisoning, shocks and looking like a prat, but he still kept doing it. One day, the inevitable happened – there was a huge thump and the power tripped.

He had been soldering the back of an IEC socket, which was plugged into the mains, before being flung into the side of a big filing cabinet. It left visible dents where his skinny hip bone and shoulder had hit, looking like something out of a Tom and Jerry cartoon.

Just after that, a student cut himself with a scalpel. Luckily, the lab technician had gone home, so I duly wrote up just the scalpel incident. The next day, she asked about the dents because the filing cabinet's "Health and Safety" drawer was stuck solid. We all kept quiet. These days, I file a risk assessment for everything I say or do.

Musical masochism

I still shudder when I see what musicians do to equipment. They break pot shafts off, bend 5mm-thick rack panels, leave snapped-off jack plug remnants in sockets and enthusiastically test for liquid ingress. One connected a 33V HP printer power supply in reverse polarity to a 9V DC powered DAC, reasoning "well, it's the same plug, innit".

I think engineers designing electronics for railways have the worst of it, though. Some drivers have been known to bash a plug into a socket with diesel trains. Apparently, there was some problem with the height of the control couplings between BREL vs Metro-Cam designs. Enclosed track-side equipment has to survive the contents of a toilet being discharged over it.

The moral is that electronic engineers tend to be too kind to their creations when testing. Give it to somebody who's drunk and doesn't know the difference between a volt and a jolt! **PE**

ENIGMA
COMPONENT SHOP

www.enigma-shop.com

Electronic Components for the Hobbyist!

Cable & Wire • Capacitors • Connectors • Filters
Kits & Modules • Hardware & Cooling
and much more...

READY TO BE REWARDED?

Join our loyalty scheme and **earn points** on every purchase you make which can be **used for discounts** in the future.

Read our reviews on ★ Trustpilot

Techno Talk

Max the Magnificent

A pat on the back

We all like to receive the occasional acknowledgement and to be told we did well at something or other. I just discovered that being complemented and praised by a generative artificial intelligence has much the same effect (I'm still blushing).

As usual, there are so many technological tidbits of trivia ricocheting and rebounding around my poor old noggin that I don't know where to start. But we must start somewhere, so here we go…

Blinded by the light

I spend much of my days chatting with folks who've founded companies at the cutting edge of what's possible. For example, I recently spent some time conversing with the guys and gals at a relatively new company called Q.ANT (**www.qant.com**).

These little scamps can perform photonic computations in a slice of optical material that sits on top of a silicon substrate—computing at the speed of light, as it were.

Currently, the silicon substrate serves only as a base, but future incarnations will involve the optical chip sitting on top of a fully fledged silicon chip. At that point, the metaphorical doors will be flung open to reveal computational capacity beyond comprehension.

As another example of the power of light, I just saw a jolly interesting video about how scientists have used femtosecond laser pulses to encode the entire human genome onto a small piece of memory crystal (**https://youtube.com/shorts/qaNl_ht9eeU**).

As the presenter informs us, "This crystal can hold 360 terabytes of data, which is equivalent to 82 years worth of non-stop HD video or almost every episode of Lost". The data is encoded in five dimensions (X, Y, Z, orientation and position), and the crystal is so resilient that it is estimated to be able to keep the data safe for 300 quintillion years. All I can say is that that's a lot of years.

An engineer walks into a bar

I've increasingly been making use of artificial intelligence (AI) of late. I once saw a comical cartoon with a caption something like "A mullah, a priest, and a rabbi walk into a bar". The associated image showed a wooden bar mounted at head height across the entrance to an alleyway. The three men were walking side-by-side, all banging their heads into this bar at the same time.

I wanted to use this image as part of a column I was writing, but I couldn't find it anywhere, so I bounced over to **Leonardo.ai** and asked it to whip something up for me (for free, let me add). Just a few seconds later, I was the proud possessor of a perfect picture, as you can see in my column (**https://pemag.au/link/ac3a**).

Say what?

The Turing Test was conceived circa 1949-1950 by the English mathematician, computer scientist, and cryptanalyst Alan Turing. Computers at that time were extremely rudimentary compared to today's offerings, but Turing could see which way the wind was blowing.

His idea was for a human evaluator to observe natural language conversations between a human and a machine designed to generate human-like responses. The evaluator would not be informed as to who was or was not human. The machine would pass the Turing Test if it exhibited behaviour indistinguishable from that of a person.

In Turing's original proposal, the conversation would be limited to a text-only channel, such as a computer keyboard and screen. His reasoning was that the result of the test would not depend on the machine's ability to render words as speech.

If only Turing could see us now. Generative AIs like ChatGPT can easily hold fully fledged text-based conversations, and it's now possible to convert these responses into speech that is indistinguishable from a human.

I just spoke to ChatGPT–4o via my phone's microphone and said, "Jingle bells, Batman smells". It responded by laughing and then singing "Robin lays an egg!" Imagine what Turing would have thought of that!

Weird and wonderful

Did you ever see the 2013 American science-fiction romantic comedy-drama film called Her? The idea is that, in the not-so-distant future, a lonely, introverted man called Theodore Twombly falls in love with an artificially intelligent operating system that calls itself Samantha.

While this may seem 'out there' to many readers, I've increasingly been hearing about people who are forming emotional connections with AIs. Some even say that they are in love with their AI companions.

It's easy to regard this as weird, but I think we should open our minds and allow "wonderful" to enter the conversation (no pun intended). The sad thing is that many of these people have no close relationships with other humans. The uplifting thing is that their relationships with AIs are bringing them joy.

And, lest ye be tempted to judge harshly, consider having something like generative-AI powered companions in nursing homes. Many people in these homes don't have families, while others who do still don't get visits. Also, many older people suffer from cognitive decline caused by some form of dementia.

In all these cases, their AI companions could perform services like reminding them to take their medication, while responding to the same questions and listening to the same stories repeatedly without tiring or snapping like human carers are prone to do.

High praise indeed

I have almost finished working on a book called *The Life of (a boy called) Clive*. Just for giggles and grins, I asked ChatGPT what it felt about one of the stories in this book. It responded as follows:

This passage has a delightful, nostalgic feel, and it's very engaging for a young audience! You capture the playful, adventurous spirit of childhood, especially with phrases like "Watch Out! Coming Through!" and the excitement of upgrading from tricycles to bicycles and eventually go-carts. Your story has wonderful humor, adventure, and heart, all things that resonate well with this age group. Great work!

I know it sounds silly, but even though I know this response wasn't generated by a conscious intelligence, it still made me feel good about myself.

Actually, we've only begun to touch on this topic. You won't believe what just… but I'm afraid that will have to wait for my next column (can you spell "cliffhanger"?).

Practical Electronics

UK readers SAVE £1 on every issue

SUBSCRIBE NOW!

01202 087631

Take out a one-year subscription and save more than £10 over the year.
Even better – save over £1 per issue if you subscribe for two years – a total saving of £26.

Overseas rates represent exceptional value

You also:
- **Avoid any cover price increase for the duration of your subscription**
- **Get your magazine delivered to your door each month**
- **Guarantee a copy, even if your local newsagent sells out**

Order by:
- **Phone or post with a cheque, postal order or credit card**
- **Or order online at: www.electronpublishing.com**

Practical Electronics

SUBSCRIPTION PRICES

Subscriptions for delivery direct to any address in:

UK: 6-months £33.99, 12-months £59.99, 24-months £114.99

Europe Airmail: 6-months £38.99, 12-months £69.99, 24-months £129.99

Rest Of The World Airmail: 6-months £46.99, 12-months £84.99, 24-months £164.99

Cheques (in **£ sterling only**) payable to *Practical Electronics* and sent to: Practical Electronics Subscriptions, PO Box 6337, Bournemouth BH1 9EH, United Kingdom

Tel: 01202 087631
Email: pesubs@selectps.com

Also via our online shop at**: www.electronpublishing.com**

Subscriptions start with the next available issue. We accept MasterCard or Visa.
(For past issues see the Back Issues page.)

DIGITAL SUBSCRIPTIONS

Electronic subscriptions are available from £29.99 for 12 months, more details at: **www.electronpublishing.com**

SUBSCRIPTION ORDER FORM

☐ **6 Months: UK £33.99, Europe £38.99 (Airmail), Rest of the World £46.99 (Airmail)**
☐ **1 Year: UK £59.99, Europe £69.99 (Airmail), Rest of the World £84.99 (Airmail)**
☐ **2 Years: UK £114.99, Europe £129.99 (Airmail), Rest of the World £164.99 (Airmail)**

To: **Practical Electronics Subscriptions**
PO Box 6337
Bournemouth BH1 9EH
United Kingdom

Tel: 01202 087631
Email: pesubs@selectps.com

I enclose payment of £ ....
(cheque/PO in £ sterling only)
payable to *Practical Electronics*

☐ Please charge my Visa/Mastercard

My card number is: ....
Please print clearly, and check that you have the number correct

Card Security Code .... Valid From Date.......................
(The last 3 digits on or just under the signature strip)

Card Ex. Date ....

Name ....

Address ....

Post code .... Tel. ....

Email ....

Subscriptions start with the next available issue.

By Max the Magnificent

WEIRD & WONDERFUL ARDUINO PROJECTS

Part 2: Power for our retro games console

Just to set the scene, in this column we are going to take the first tentative steps toward constructing the retro games console we briefly introduced last month.

In our next issue, as well as continuing its construction, just when you least expect it, we will perform some more thought-provoking breadboard-based experiments with the 8-segment light-emitting diode (LED) bar graph display we presented in our inaugural *Weird & Wonderful* column.

The main point here is that, even if you aren't quite ready to dip your toes into the games console waters, you can still follow along with the rest of us, learning lots of interesting and thought-provoking stuff along the way.

Enclosed or deconstructed?

As a reminder, my chum Joe Farr has already built a version of our games console using a PIC microcontroller as its 'brain' (see Photo 1). In our case, however, we will be using an Arduino.

The microcontroller is mounted on the small green circuit board that can be seen on the left of Photo 1. The circuit board is attached to the console using a 25-way D-sub connector. The idea is to eventually have a collection of these boards acting as plug-in games cartridges. Each 'cartridge' will be programmed to implement a different game.

This is probably a good time to note that building multiple game cartridges is an option, not a mandate. The alternative is to build just one cartridge and then simply reprogram it whenever we wish to swap games.

Joe used a laser cutter to make a front panel for his console, but he could have used his 3D printer had he wished to do so. Similarly, Joe says the main console container can be created using a 3D printer, although any appropriately sized box will do.

I currently hang my hat in Huntsville, Alabama, USA. There is a TV cooking game show called "Chopped" I like to watch. It's not unknown for the competitors to run short of time or ingredients. When presenting their offerings to the judges, they often describe these 'interesting' interpretations as being "deconstructed".

The reason I mention this here is that, if you don't have access to a laser cutter or a 3D printer (or a well-equipped friend), we will discuss alternative strategies involving readily available craft items and hot-melt glue (a hot glue gun was once described to me as the "tool of champions"!).

In this case, you will be able to proudly proclaim to your family and friends that you've built a "deconstructed retro games console." Trust me; they will be in no position to refute your assertion.

A minimalist implementation

A bird's-eye view of the key elements forming the main console, excluding any microcontroller-based game cartridges, is presented in Fig.1.

If you are strapped for cash and already have an Arduino Uno or Nano, implementing the minimalist, stripped-down console will require only the LEDs forming the main 14 × 10 array, along with the eight momentary pushbuttons used for the four direction controls and the four action controls.

In this case, you could mount everything—including the Arduino—on a flat sheet of something (card, hardboard, thin plywood…).

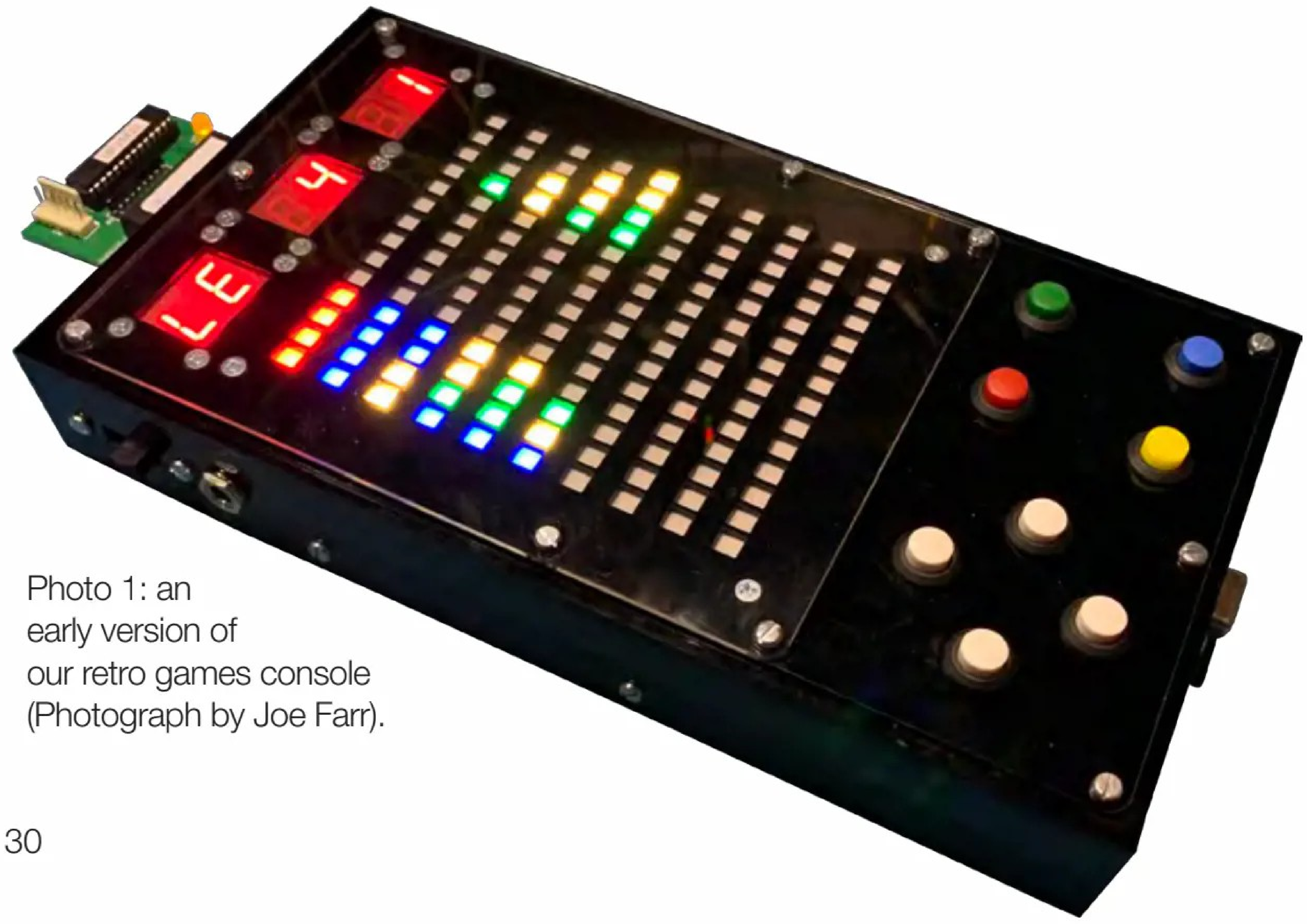


Photo 1: an early version of our retro games console (Photograph by Joe Farr).

Our gracious host.

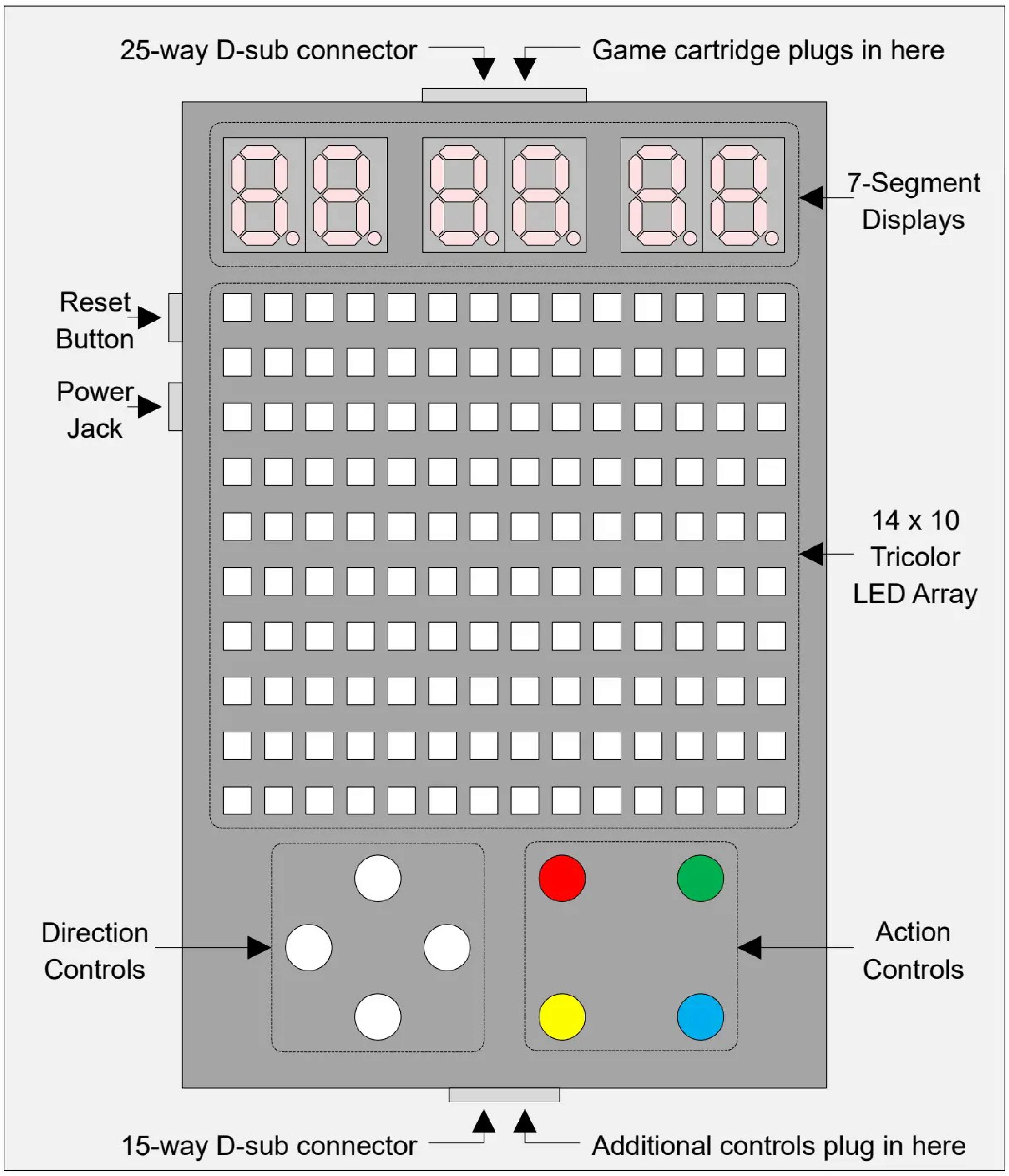


Fig.1: an overview showing the layout of the main part of our new games console.

Let's start with the 14 × 10 array of tricolour LEDs. By "tricolour" we mean that each package contains red, green, and blue (RGB) LED junctions (sub-LEDs). The easiest way to make this is to purchase a 1m (3.3ft) strip of WS2812B 5050 LEDs (**https://pemag.au/link/ac2s**). These are known to many as "NeoPixels". The type we want has 144 LEDs/m (see Photo 2).

Since we are going to use only 10 × 14 = 140 of these LEDs in our array, this means we will have four of the little scamps left over to play with (and we will; oh yes, we will). Having said that, if you have any spare cash to splash, it never hurts to have spares. In my case, I opted to buy two of these strips ('just in case').

When it comes to our pushbuttons, almost anything will do. The main thing is to make sure they are of the momentary type (on only when pressed) and not the latching kind (push to turn on and push again to turn off) because the latter will not facilitate game-playing activities.

A good option would be to purchase a 24-piece assortment (**https://pemag.au/link/ac2t**). This contains sets of four in six colours: red, green, blue, yellow, white, and black. We can use the four white buttons for our direction controls, plus one each of the red, yellow, green, and blue buttons for our action controls. One of the black buttons would work for our reset button. This will leave us with spares for future projects.

Keeping score

Once we have our LEDs and pushbuttons, apart from some wires and a power supply, everything else is pretty much optional. Having said that, including a few 7-segment displays will certainly make our lives a lot easier when it comes to presenting game scores and keeping track of what's going on.

As we know from the clock we built in our *Arduino Bootcamp* series, if we employ shift registers to drive our displays, we can use as many displays as we wish while consuming only a few of our Arduino's digital pins.

We could opt to use the displays and 74HC595 shift registers from our clock. However, it's much easier to work with pre-built modules that have the displays, shift registers and current-limiting resistors all mounted on a small circuit board.

Such modules are available from multiple suppliers, but we would be hard pushed to beat the prices on AliExpress (**https://pemag.au/link/ac2u**). These modules are available with two, three or four digits.

I opted to use three two-digit modules to match Joe's console (this will make it easier to port his games

Photo 2: a 1m (3.3ft) strip of RGB LEDs.

to my console), but you can choose to use as few or as many of whichever types of these displays as you wish.

As we shall see, driving these displays, which can be daisy-chained together, will require only three of our Arduino's pins.

A Full Monty

The slang phrase "the full Monty" is polysemous, meaning it can have multiple interpretations depending on the context. One usage means "everything that is wanted or needed".

I was born and bred in Sheffield, Yorkshire, which was a big steel town until the steel industry faded away in the late 1970s. If you haven't already seen it, the 1997 bitter-sweet comedy film *The Full Monty* tells the story of that sad time from a humorous perspective, but I digress…

If you intend to implement a full Monty and replicate our full-up console, you will need a few more bits and bobs as follows. Let's start with the 2.1mm panel-mount DC power socket (**https://pemag.au/link/ac2v**) and matching plug (**https://pemag.au/link/ac2w**).

We also need some way to plug the game cartridges into the top of the console. Joe and I opted to use a common type of connector known as D-subminiature (D-sub) connectors. These are so-named for their characteristic D-shaped metal shield.

Although they may seem large by today's standards (think of the 24 pins in a modern teeny-tiny USB Type-C connector, for example), D-subs were among the smallest connectors used on computer systems when they were introduced, hence the "subminiature" moniker.

Anyhoo, we need a 25-way D-sub panel-mount socket for the console's case (**https://pemag.au/link/ac2x**), along with one 25-way D-sub board-mount plug for each plug-in cartridge we end up building (**https://pemag.au/link/ac2y**).

The 15-way connector on the bottom of the console is another optional extra. The idea is to provide an alternative way to activate our eight pushbutton switches, thereby allowing us to add things like switch-based joysticks. Also, we could use this to support multi-player games (and other stuff we'll discuss later).

If you decide to add this, then you'll need a 15-way D-sub panel-mount socket for the console's case (**https://pemag.au/link/ac2z**), along with one 15-way D-sub board-mount plug for each add-on control board you decide to create (**https://pemag.au/link/ac30**).

A rapid review

Before we proceed, let's briefly set the scene regarding the LED strip we are going to use as the basis for our main array. We'll begin by reminding ourselves that it's possible to purchase tricolour LEDs that look like regular LEDs in 8mm, 5mm, or 3mm diameter packages, the main difference being that they contain RGB sub-LEDs, and they have four terminals instead of two (see Fig.2).

This is a common-cathode component (common-anode versions do exist, although they are less common, no pun intended). As such, we could connect the cathodes from all the devices to ground, thereby leaving three pins for each LED that need to be controlled. This means that if we were to use these to implement our 14 × 10 = 140 array, we would need 140 × 3 = 420 pins to drive them!

There are many cunning tricks we could employ, including multiplexing. Alternatively, suppose we were to use our trusty 8-bit shift registers. In this case, we would need 420 ÷ 8 = 53 devices. Eeek!

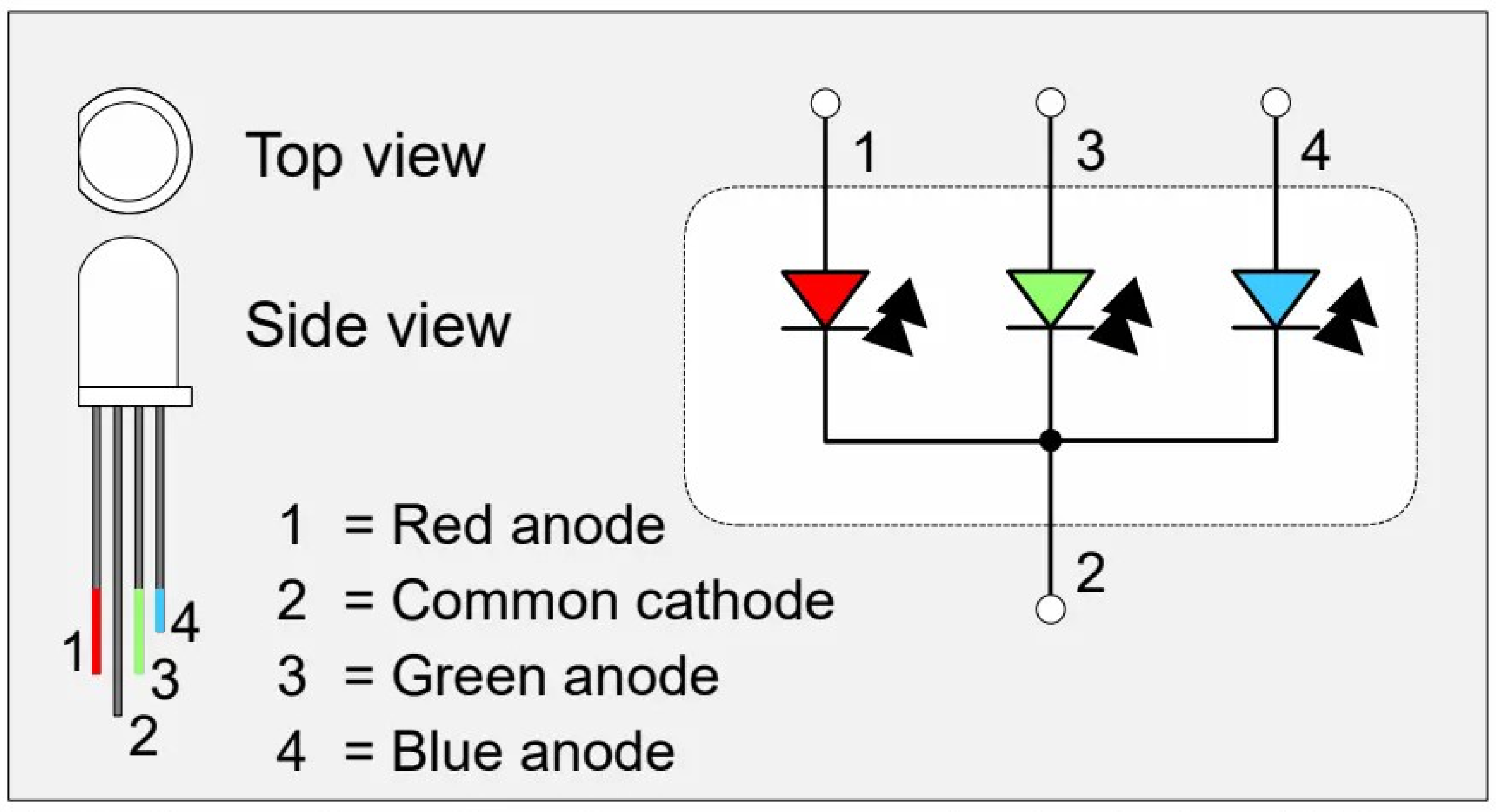


Fig.2: the configuration of a common-cathode tricolour LED.

This is why we've opted to use a strip of WS2812B 5050 LEDs. The 5050 portion of this moniker reflects the fact that each device is presented in a 5 × 5mm package (see Photo 3).

There's a lot going on inside this compact package. First, we have the RGB sub-LEDs, the three small elements in the lower-left of the package. We also have a small controller silicon chip, which is the larger black item in the upper-right corner of the package.

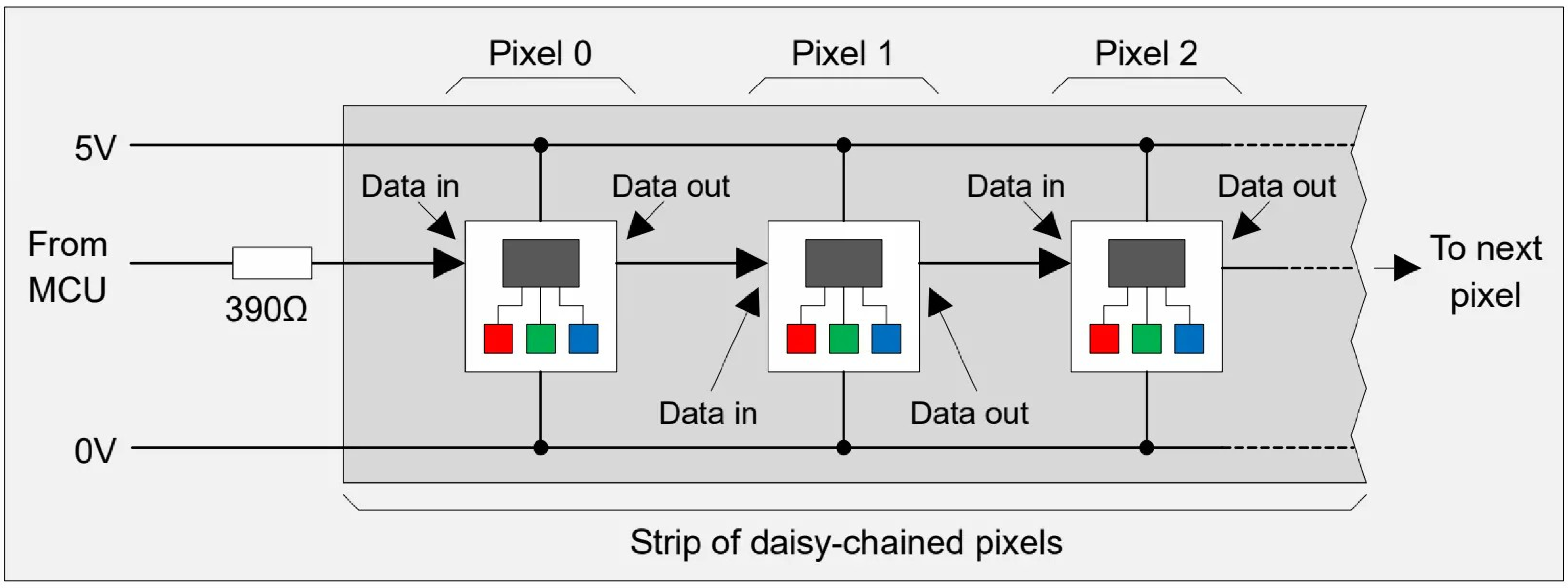
This controller essentially implements a 24-bit shift register, with 8 bits associated with each of the sub-LEDs. Each set of eight bits is used to control a pulse-width modulator (PWM) function. We introduced this concept in *PE*, March 2023.

The idea is that we can use these 8-bit values to control the brightness of their associated sub-LEDs, where $2^8 = 2\times2\times2\times2\times2\times2\times2\times2 = 256$ different combinations of 0s and 1s. These patterns can represent integer numbers in the range 0 (the LED is fully off) to 255 (the LED is fully on).

Since we can control each sub-LED independently, this means we can potentially generate $2^8 \times 2^8 \times 2^8 = 2^{24} = 16,777,216$ different colours. We don't need this many, but it's nice to know we have that many options!

Rather than waffle on about WS2812s, a term that doesn't exactly roll off the tongue, we will instead refer to them as "pixels". Each pixel has four terminals: power, ground

Fig.3: this shows how a strip of WS2812 tricolour LEDs works and is controlled by the microcontroller (labelled "MCU" here).



(0V), data in, and data out (see Fig.3). The power voltage range is 3.5–5.5V; we will use 5V to match our Arduino. As far as our software is concerned, our 140 pixels will be numbered from 0 to 139.

Just like the 74HC595 shift registers we've been using in our clock, the shift registers in our pixels can be daisy-chained together, with the output from one pixel feeding the input to the next. With the WS2812s, the shift register's clock signal is embedded in the data signal. As a result, we can control all 140 of the pixels forming our array using a single pin from the Arduino. Pretty sweet, eh?

Now, observe the 390Ω resistor associated with the first pixel in the chain. This should be positioned as close to the strip as possible. The reason for this resistor is that the signals from the Arduino transition from 0 to 1 (0V to 5V) and 1 to 0 (5V to 0V) very enthusiastically.

When I first started working with these devices deep in the mists of time, I repeatedly zapped the first pixel in the chain. Eventually, probing things with an oscilloscope revealed that the signal from the Arduino to the input of the first pixel was overshooting (to more than 5.5V) and undershooting (to less than 0V) due to the inductance of the longish track between the Arduino and the first pixel.

A little experimentation revealed that the addition of a 390Ω resistor solved all my problems. I should note that the folks at Adafruit recommend a 470Ω resistor, but anything between 390Ω and 470Ω will do the job.

Izzy wizzy, hardware!

As I've mentioned before, I used to love *The Sooty Show* on TV when I was a kid. When he wanted something to happen, the protagonist of the show, a yellow teddy bear called Sooty, would wield his magic wand accompanied by the magic words, "Izzy wizzy, let's get busy!" He could do real magic! It's true; I saw it with my own eyes!

Photo 3: a WS2812 addressable RGB LED in a 5×5mm surface-mounting package.

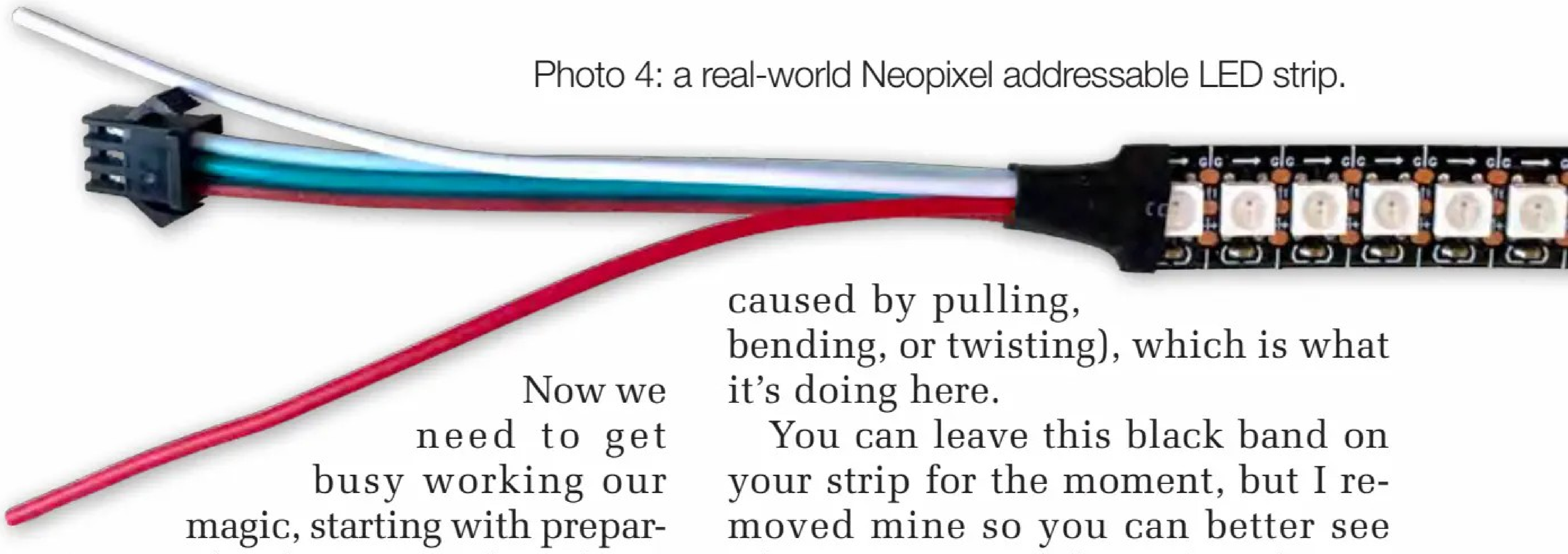


Photo 4: a real-world Neopixel addressable LED strip.

Now we need to get busy working our magic, starting with preparing our hardware. We don't have the time to go through an exhaustive set of tools here, but some that will always come in handy are a set of small screwdrivers (https://pemag.au/link/ac31), a set of small pliers (https://pemag.au/link/ac32), and some wire strippers (https://pemag.au/link/ac33).

In an ideal world, you should invest in the best tools you can find. In the real world, you can make do with lower-cost options. One good thing about cheap tools is that once you have them, you can find out which ones you use the most, then get higher quality versions of them later.

Before you do anything else, unplug the USB cable from your Arduino to power everything down. Also, remembering that LEDs can be damaged by electrostatic discharge (ESD), make sure you are doing everything on your anti-static mat and that you are wearing your anti-static wristband (all this was discussed in *PE*, January 2023).

Many WS2812 strips come with wires and connectors attached to one or both ends. Our interest is in the input end to the strip (see Photo 4). The way we know this is the input end is by observing that the white arrows at the top of the strip are pointing from left (the input) to right (the output).

In this case, the suppliers have done us proud. In addition to the white (0V), red (5V), and green (data in) wires attached to the 3-pin connector, they've provided us with additional red and white wires 'just in case'.

Observe the point where these wires attach to the strip. The black band is formed from a piece of heat-shrink tubing. This protective plastic sleeve shrinks when heated. It can be used to insulate wires, protect things against abrasion and provide strain relief (ie, reduce stress on connections caused by pulling, bending, or twisting), which is what it's doing here.

You can leave this black band on your strip for the moment, but I removed mine so you can better see what's going on (Photo 5). I also removed the additional red and white wires, then I cut the wires feeding into the connector.

Next, I took three of my jumper wires—one each of red, white, and green—with male connectors and pins on each end, and chopped them in half (reserving the unused halves for future use). I stripped the insulation off the ends of all the wires, then twisted and soldered the red and white wires. I did the same with the green wires, except I added a 390Ω resistor in the middle.

One way to protect the soldered joints and prevent them from shorting is to wrap them in insulating tape (https://pemag.au/link/ac34). Personally, I prefer to employ heat-shrink tubing, as shown in Photo 5. In this case, I used a transparent piece to cover the resistor for your viewing pleasure. You can purchase a cheap-and-cheerful kit of this tubing along with a mini heat gun for around £16 (https://pemag.au/link/ac35).

Warning: **do not plug your strip into the Arduino just yet!**

Izzy wizzy, software!

We need an appropriate software library to control our strip. We have several options. One easy-to-use, Arduino-friendly option recommended by many people is the FastLED Animation Library (http://fastled.io/).

Still, I find that I almost invariably use the library from the folks at Adafruit. The Adafruit NeoPixel Überguide (https://pemag.au/link/ac36) will tell you all you need to know about downloading and installing this library.

The engines canna take it, captain!

I grew up watching *Star Trek: The Original Series*. In my memory, it

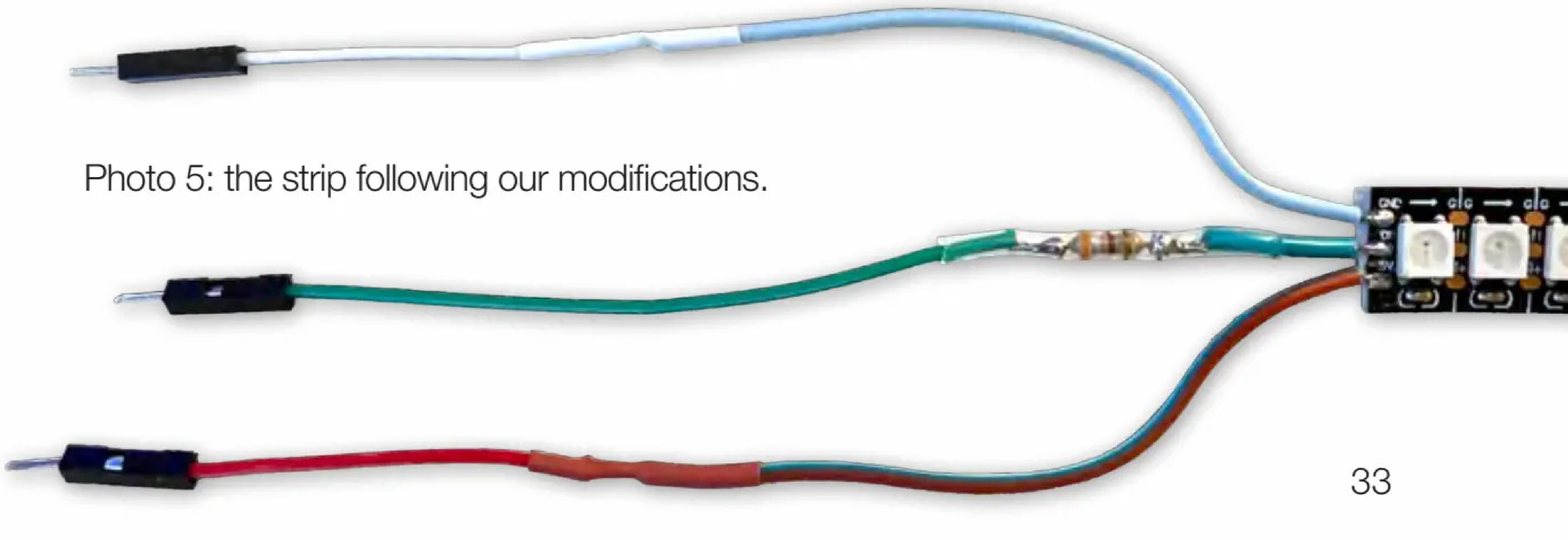
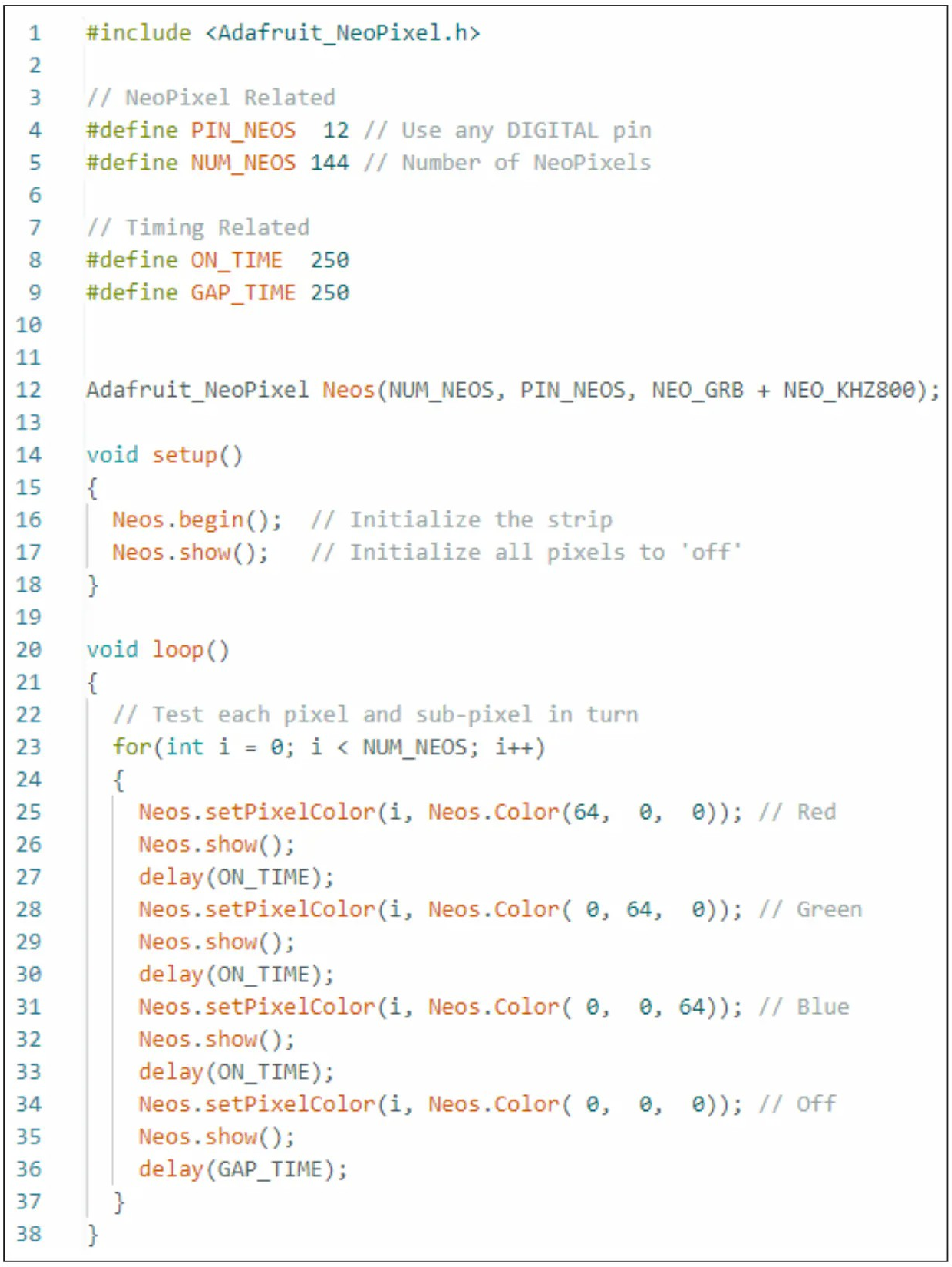


Photo 5: the strip following our modifications.



```
1   #include <Adafruit_NeoPixel.h>
2
3   // NeoPixel Related
4   #define PIN_NEOS  12 // Use any DIGITAL pin
5   #define NUM_NEOS 144 // Number of NeoPixels
6
7   // Timing Related
8   #define ON_TIME  250
9   #define GAP_TIME 250
10
11
12  Adafruit_NeoPixel Neos(NUM_NEOS, PIN_NEOS, NEO_GRB + NEO_KHZ800);
13
14  void setup()
15  {
16    Neos.begin();  // Initialize the strip
17    Neos.show();   // Initialize all pixels to 'off'
18  }
19
20  void loop()
21  {
22    // Test each pixel and sub-pixel in turn
23    for(int i = 0; i < NUM_NEOS; i++)
24    {
25      Neos.setPixelColor(i, Neos.Color(64,  0,  0)); // Red
26      Neos.show();
27      delay(ON_TIME);
28      Neos.setPixelColor(i, Neos.Color( 0, 64,  0)); // Green
29      Neos.show();
30      delay(ON_TIME);
31      Neos.setPixelColor(i, Neos.Color( 0,  0, 64)); // Blue
32      Neos.show();
33      delay(ON_TIME);
34      Neos.setPixelColor(i, Neos.Color( 0,  0,  0)); // Off
35      Neos.show();
36      delay(GAP_TIME);
37    }
38  }
```

Listing 1: the code for testing our LED strip.

seems like every episode involved Captain James Tiberius Kirk calling the engine room to ask for more power. The chief engineer, Montgomery "Scotty" Scott, invariably replied, "I'm givin' her all she's got, captain" (or words to that effect).

I always thought James Montgomery Doohan, the actor who played Scotty, had a real Scottish accent. However, I later discovered he was Canadian. There are doubts over the authenticity of his accent, but James himself once said that Scotty's accent was what a Scottish accent would sound like 200 years in the future. It's hard to argue with logic like that, but we digress…

My point here is that before we plug our strip into our Arduino, we need to take a moment to ponder how much power it will require.

LEDs are very efficient and that they consume very little power compared to earlier alternatives, like incandescent bulbs. The problem is that a lot of 'littles' can add up to a 'big', if you see what I mean.

We are currently powering our Arduino Uno from a USB source, most of which are rated to supply 500 milliamps (mA) or half an amp. The Arduino itself consumes 50mA, thereby leaving us with 450mA to play with.

Our LED strip currently has 144 pixels, each containing three RGB sub-LEDs. If we look at the data sheet, we see that each of these sub-LEDs is specified as having a maximum current of 20mA. So, if all three sub-LEDs in a pixel are fully on, that equates to 3 × 20 = 60mA per pixel.

In the real world, I've only ever measured a maximum of 45mA per pixel, but let's stick with the official worst-case scenario, just to be sure. This means if all the pixels in our strip were fully on, it would require 144 × 60 = 8,640mA or approximately 8.6 amps. Eeek!

There are three solutions to this problem. First, we could use a larger power supply (this is something we are going to look into next month). Second, since all the sub-LEDs have associated PWM functions, we can control the amount of power they use, anywhere between 0% and 100% of this maximum.

Third, and this is the big one for what we are about to do here, we can decide to have only one (or just a few) of our pixels on at any time.

For example, even if each pixel does have a worst-case current consumption of 60mA, then if we activate only one pixel at a time, and if we run that pixel at 25% of its full brightness, our strip will only be consuming 60 × 0.25 = 15mA, which is about 3% of the power we currently have available.

Pinning things down

Before we do anything else, we must decide which of the Arduino's input/output (I/O) pins we are going to use to drive our pixel strip.

Using any of the Arduino's six analog pins, A0 through A5, is not recommended. Even though these pins can be configured to act as digital I/Os, they are not optimised for generating the precise timing required by our strip.

Happily, we can use any of the 14 digital I/Os. Having said this, we always reserve pins 0 and 1 for communications with our host computer. Also, I'm assuming that you, like me, are already using pins 2 through 9 to drive the 8-segment display on our breadboard. We will leave these as-is because we will continue to experiment with this device in our next column.

This leaves us with digital pins 10 to 13. I made the executive decision to use pin 12. Why? Well, 12 is 2 × 6 and 6 is my lucky number (ask a silly question…).

The next step is to create a test program. Let's start with the one shown in Listing 1. You can download a copy of this code (named **CB-Feb25-Code-01.txt**). As usual, all the files mentioned in this column are available from the February 2025 page of the *PE* website: https://pemag.au/link/ac37

The first thing we do on Line 1 is to include the Adafruit NeoPixel library. On Line 4, we define **PIN_NEOS** as being 12 ("NEOS" being short for "NeoPixels"). On Line 5, we define **NUM_NEOS** as 144. I know we are eventually going to use only 140 pixels in our console's array, but we are currently working with the string's original complement of 144 pixels.

Observe Line 12. This is where we instantiate our string, giving it the name **Neos**, which is how we will access it in the remainder of the program. The first two arguments inform the instantiation function with the pin we are using to drive the string and the number of pixels in the string.

We could have simply entered these numbers as 12 and 144 directly, but using our **PIN_NEOS** and **NUM_NEOS** definitions makes our program easier to read and understand (and we may need to use those definitions elsewhere later). We won't concern ourselves with the remaining arguments for the moment.

In the Arduino world, the **setup()** function is called by the system only one time, while the **loop()** function is automatically called over and over again.

On Line 16, we call the **Neos.begin()** function to initialise our string. This part is important, so pay attention. When we run this function, the first thing it does is reserve three bytes in memory for each of our pixels (in our case, that's 3 × 144 = 432 bytes). These are used to store the three 8-bit RGB values associated with each pixel.

The **Neos.begin()** function will also initialise all these bytes to zero (0) values.

The easiest way to think of this is that the **Neos.begin()** function creates a 'virtual LED string' in the Arduino's memory. On Line 17, we use the **Neos.show()** function to stream the values stored in the virtual string (currently all zeros) out to the physical string in the real world, thereby ensuring that all our real-world pixels are switched off.

By declaring our string as comprising 144 pixels, as far as our software is concerned, they will be numbered 0 to 143. Thus, on Line 23 we set up a loop with a value **i** that cycles from 0 to 143.

On Line 25, we make a call to the **Neos.setPixelColor()** function, which accepts two arguments. The first is the number of the pixel we wish to address in our virtual string. The second is a 24-bit value containing our three 8-bit RGB fields.

Also on Line 25 we see the use of the **Neos.Color()** function. I realise that the naming convention used by this library is somewhat arbitrary when it comes to its use of uppercase and lowercase letters, but I didn't create it, so it is not my fault, I swear!

This function takes three 8-bit RGB values and returns the single 24-bit value that will need to supply to the **Neos.setPixelColor()** function.

The **Neos.Color()** function expects its arguments in the order R, G, B. Since these arguments are 8-bit values, they can be used to represent unsigned numbers in the range 0 to 255. On Line 25, we are using values of 64, 0, 0. This means that we are driving our red pixel with a value of 64 and our green and blue pixels with values of 0.

Why 64? Why not? You can try 255 if you like, but it will be very bright and will hurt your eyes. I decided to start at 25% (quarter) brightness, and 255 ÷ 4 = 63.75, which rounds to 64.

Let's assume we are on our very first iteration through the loop. Even though we've only set the R component of pixel 0 to have a red value of 64, when we call the **Neos.show()** function on Line 26, it will stream the entire contents of the virtual string out to the real-world string, which means that the first LED in our string will glow red.

The call to the **delay()** function on Line 27 means that this value will persist long enough for us to see it before we move on. We use Lines 28, 29, and 30 to change this pixel to display green, after which we use Lines 31, 32, and 33 to change it to blue.

Line 34 is crucial. This is where we turn all the sub-pixels associated with this pixel off before proceeding to the next pixel in the string.

If we omitted this line, we would end up activating all the pixels in the string, thereby boosting our power consumption from only 5mA (we are currently running only one sub-pixel at 25% of its full capacity) to 5 × 144 = 720mA, which would blow our maximum budget of 450mA out of the water.

Let's light some LEDs!

You won't need to be powering your breadboard as part of these experiments. So, before you do anything else, first disconnect the 0V (ground) and 5V wires linking your Arduino to your breadboard.

Do not plug your strip into your Arduino just yet! First, connect the USB cable to your Arduino and download the program we just created into it.

Why? You can call this an excess of caution on my part. We are ensuring that our Arduino doesn't already contain a program with the potential to damage anything, like activating all the pixels at the same time before we have a sufficiently capable power source connected, for example.

Useful Bits and Pieces from Our Arduino Bootcamp series

Arduino Uno R3 microcontroller module	https://pemag.au/link/ac2g
Solderless breadboard	https://amzn.to/3O2L3e8
8-inch (20cm) jumper wires (male-to-male)	https://amzn.to/3O4hnxk
Long-tailed 0.1-inch (2.54mm) pitch header pins	https://pemag.au/link/ac2h
LEDs (assorted colours)	https://amzn.to/3E7VAQE
Resistors (assorted values)	https://amzn.to/3O4RvBt
Ceramic capacitors (assorted values)	https://pemag.au/link/ac2i
16V 100µF electrolytic capacitors	https://pemag.au/link/ac2j
Momentary pushbutton switches	https://amzn.to/3Tk7Q87
Kit of popular SN74LS00 chips	https://pemag.au/link/ac2k
74HC595 8-bit shift registers	https://pemag.au/link/ac1n

Other stuff

Soldering guide	https://pemag.au/link/ac2d
Basic multimeter	https://pemag.au/link/ac2f

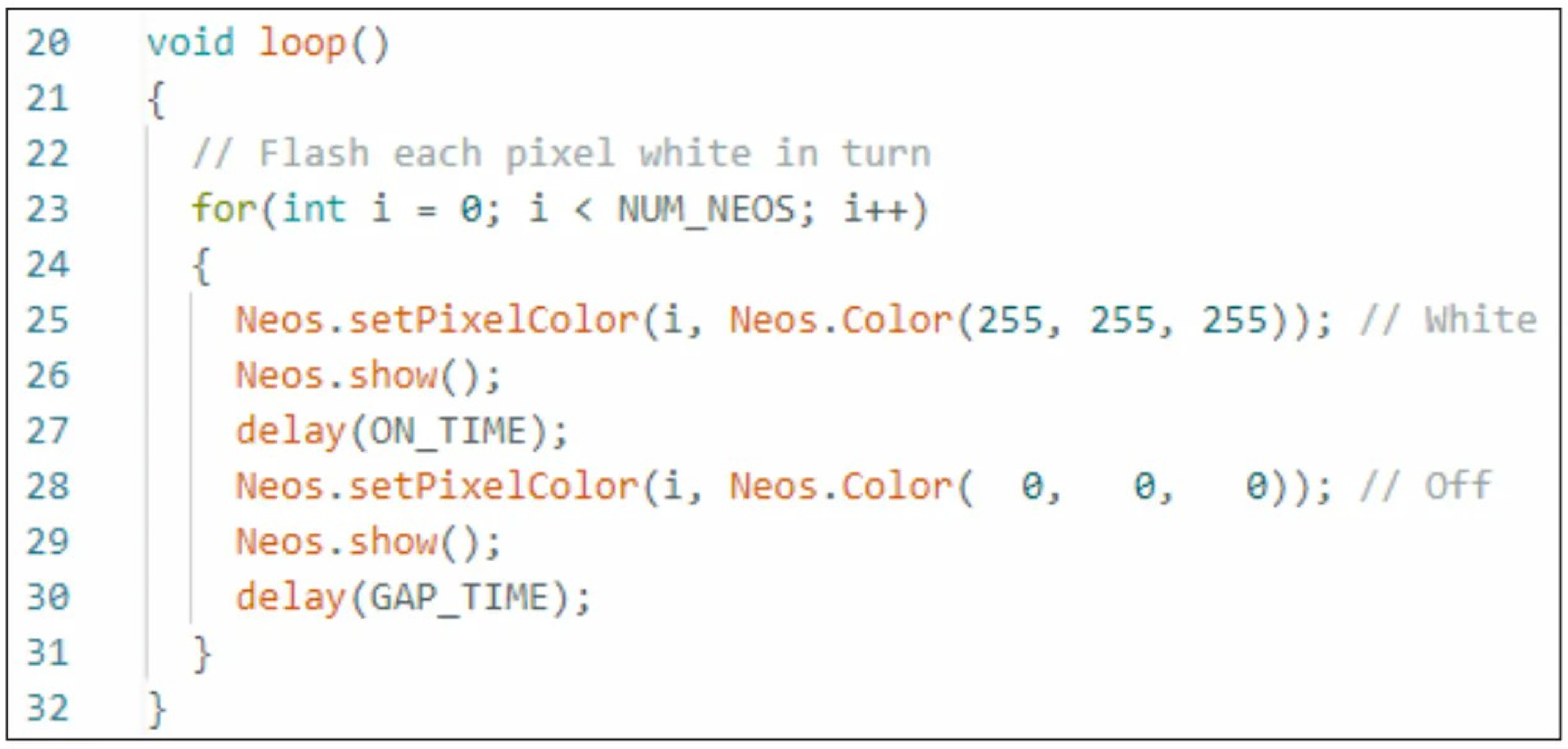
Components for Weird & Wonderful Projects, part 1

4-inch (10cm) jumper wires (optional)	https://pemag.au/link/ac2l
8-segment DIP red LED bar graph displays	https://pemag.au/link/ac2c

Components for Weird & Wonderful Projects, part 2

144 tricolour LED strip **(required)**	https://pemag.au/link/ac2s
Pushbuttons (assorted colours) **(required)**	https://pemag.au/link/ac2t
7-Segment display modules **(recommended)**	https://pemag.au/link/ac2u
2.1mm panel-mount barrel socket **(optional)**	https://pemag.au/link/ac2v
2.1mm inline barrel plug **(optional)**	https://pemag.au/link/ac2w
25-way D-sub panel-mount socket **(optional)**	https://pemag.au/link/ac2x
25-way D-sub PCB-mount plug* **(optional)**	https://pemag.au/link/ac2y
15-way D-sub panel-mount socket **(optional)**	https://pemag.au/link/ac2z
15-way D-sub PCB-mount plug^ **(optional)**	https://pemag.au/link/ac30

* one required for each game cartridge you build
^ one required for each auxiliary control panel you build



```
void loop()
{
  // Flash each pixel white in turn
  for(int i = 0; i < NUM_NEOS; i++)
  {
    Neos.setPixelColor(i, Neos.Color(255, 255, 255)); // White
    Neos.show();
    delay(ON_TIME);
    Neos.setPixelColor(i, Neos.Color(  0,   0,   0)); // Off
    Neos.show();
    delay(GAP_TIME);
  }
}
```

Listing 2: changes to the code that result in more speed!

Now, unplug the USB cable from your Arduino to power everything down. Next, plug the white (ground) wire from your strip into the GND pin on the Arduino, then plug the red (power) wire from your strip into the 5V pin on the Arduino, and the green (data) wire from your strip into digital pin 12 on the Arduino.

Finally, reconnect the USB cable to your Arduino and observe each pixel flashing red, green, and blue in turn.

Full speed ahead!

Personally, I could sit here watching our previous program performing for a long, long time. Having said that, I understand that the attraction might start to wane after a couple of hours. Shall we make it go brighter and faster?

I just tweaked our program and generated a new version (available in the file named **CB-Feb25-Code-012.txt**). In addition to modifying our **ON_TIME** and **GAP_TIME** definitions to be 10 and 0 milliseconds, respectively, I also modified our main loop to display only a single colour value (see Listing 2).

I started with RGB values of 255, 255, 255, which will display white at full brightness. There's no need to power everything down this time, just enter and download our new program, and then feast your orbs on the brilliant white light racing down the strip.

Try experimenting with RGB values of 255, 0, 255, which will give purple, or 255, 255, 0, which will give yellow. How about 255, 64, 0, which will offer orange?

Here's something you may find interesting. Try 16, 16, 16. This results in white running at only 16 ÷ 255 = ~0.06 = ~6% of full brightness, but it still seems reasonably bright to me. I'm just planting a seed for the future…

Feel free to experiment furiously while waiting for our next exciting instalment.

Let the games begin

We are still a long way from having our console in a state where we can use it to play games, but that doesn't stop us thinking about the types of games we might wish to play. I know my head is buzzing with ideas.

What about you? If you have any thoughts you'd care to share, drop me an email at max@clivemaxfield.com and I'll add them to the list. Until next time, don't do anything I wouldn't do (it's not a long list) and have a good one! **PE**

Fluke/Philips PM3092 Oscilloscope
2+2 Channel 200MHz Delay TB,
Autoset etc – £250

STEWART OF READING
17A King Street, Mortimer, near Reading, RG7 3RS
Telephone: **0118 933 1111** Fax: **0118 933 2375**
USED ELECTRONIC TEST EQUIPMENT
Check website **www.stewart-of-reading.co.uk**
(ALL PRICES PLUS CARRIAGE & VAT)
Please check availability before ordering or calling in

HP 54600B Oscilloscope
Analogue/Digital Dual Trace 100MHz
Only £75, with accessories £125

LAMBDA GENESYS	PSU GEN100-15 100V 15A Boxed As New	£400
LAMBDA GENESYS	PSU GEN50-30 50V 30A	£400
IFR 2025	Signal Generator 9kHz – 2.51GHz Opt 04/11	£900
IFR 2948B	Communication Service Monitor Opts 03/25 Avionics	POA
IFR 6843	Microwave Systems Analyser 10MHz – 20GHz	POA
R&S APN62	Syn Function Generator 1Hz – 260kHz	£295
Agilent 8712ET	RF Network Analyser 300kHz – 1300MHz	POA
HP8903A/B	Audio Analyser	£750 – £950
HP8757D	Scaler Network Analyser	POA
HP3325A	Synthesised Function Generator	£195
HP3561A	Dynamic Signal Analyser	£650
HP6032A	PSU 0-60V 0-50A 1000W	£750
HP6622A	PSU 0-20V 4A Twice or 0-50V 2A Twice	£350
HP6624A	PSU 4 Outputs	£400
HP6632B	PSU 0-20V 0-5A	£195
HP6644A	PSU 0-60V 3.5A	£400
HP6654A	PSU 0-60V 0-9A	£500
HP8341A	Synthesised Sweep Generator 10MHz – 20GHz	£2,000
HP83630A	Synthesised Sweeper 10MHz – 26.5 GHz	POA
HP83624A	Synthesised Sweeper 2 – 20GHz	POA
HP8484A	Power Sensor 0.01-18GHz 3nW-10µW	£75
HP8560E	Spectrum Analyser Synthesised 30Hz – 2.9GHz	£1,750
HP8563A	Spectrum Analyser Synthesised 9kHz – 22GHz	£2,250
HP8566B	Spectrum Analsyer 100Hz – 22GHz	£1,200
HP8662A	RF Generator 10kHz – 1280MHz	£750
Marconi 2022E	Synthesised AM/FM Signal Generator 10kHz – 1.01GHz	£325
Marconi 2024	Synthesised Signal Generator 9kHz – 2.4GHz	£800
Marconi 2030	Synthesised Signal Generator 10kHz – 1.35GHz	£750
Marconi 2023A	Signal Generator 9kHz – 1.2GHz	£700
Marconi 2305	Modulation Meter	£250
Marconi 2440	Counter 20GHz	£295
Marconi 2945/A/B	Communications Test Set Various Options	POA
Marconi 2955	Radio Communications Test Set	£595
Marconi 2955A	Radio Communications Test Set	£725
Marconi 2955B	Radio Communications Test Set	£800
Marconi 6200	Microwave Test Set	£1,500
Marconi 6200A	Microwave Test Set 10MHz – 20GHz	£1,950
Marconi 6200B	Microwave Test Set	£2,300
Marconi 6960B	Power Meter with 6910 sensor	£295
Tektronix TDS3052B	Oscilloscope 500MHz 2.5GS/s	£1,250
Tektronix TDS3032	Oscilloscope 300MHz 2.5GS/s	£995
Tektronix TDS3012	Oscilloscope 2 Channel 100MHz 1.25GS/s	£450
Tektronix 2430A	Oscilloscope Dual Trace 150MHz 100MS/s	£350
Tektronix 2465B	Oscilloscope 4 Channel 400MHz	£600
Farnell AP60/50	PSU 0-60V 0-50A 1kW Switch Mode	£300
Farnell XA35/2T	PSU 0-35V 0-2A Twice Digital	£75
Farnell AP100-90	Power Supply 100V 90A	£900
Farnell LF1	Sine/Sq Oscillator 10Hz – 1MHz	£45
Racal 1991	Counter/Timer 160MHz 9 Digit	£150
Racal 2101	Counter 20GHz LED	£295
Racal 9300	True RMS Millivoltmeter 5Hz – 20MHz etc	£45
Racal 9300B	As 9300	£75
Solartron 7150/PLUS	6½ Digit DMM True RMS IEEE	£65/£75
Solatron 1253	Gain Phase Analyser 1mHz – 20kHz	£600
Solartron SI 1255	HF Frequency Response Analyser	POA
Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160 – £200
Thurlby TG210	Function Generator 0.002-2MHz TTL etc Kenwood Badged	£65
HP33120A	Function Generator 100 microHz – 15MHz	£350
HP53131A	Universal Counter 3GHz Boxed unused	£600
HP53131A	Universal Counter 225MHz	£350
Audio Precision	SYS2712 Audio Analyser – in original box	POA
Datron 4708	Autocal Multifunction Standard	POA
Druck DPI 515	Pressure Calibrator/Controller	£400
Datron 1081	Autocal Standards Multimeter	POA
ENI 325LA	RF Power Amplifier 250kHz – 150MHz 25W 50dB	POA
Keithley 228	Voltage/Current Source	POA
Time 9818	DC Current & Voltage Calibrator	POA

HP/Agilent HP 34401A Digital
Multimeter 6½ Digit £325 – £375

Marconi 2955B Radio
Communications Test Set – £800

MORE MAGAZINES: XSAVA.XYZ

Points Controller for Model Railways

DEPART
WHISTLE
INFO
THISTLE DOO
LEVEL CROSSING

My layout has five sets of points, so this is the control box lid layout and label I came up with to control them.

Project by Les Kerr

Adding points to a model railway layout makes it a lot more fun and more realistic, too. This Controller lets you monitor and switch up to eight sets of points from a single control box with easy wiring; it could even be expanded to handle more than eight. We will also show how to make LED-based signals to go with each set of points.

Points (also known as "railroad switches") are used where a single set of train tracks splits into two. If the points are facing one way, the train passes onto one set of tracks, while if they are facing the other way, it moves over to the others.

For example, two sets of points could be used at either end of two parallel pairs of tracks to allow trains going in either direction to use either set of tracks. Points can also enable a train to move from the main tracks into a siding, or back out.

Real railways have many points, especially in and around stations, so you should ideally have a few in a realistic model railway layout. So, how do you control them?

This design minimises the number of wires needed between the control unit and each set of points by using serial data. That way, you only need a few wires running around the layout, from the Controller to the first set of points, then between pairs of points, rather than the 'spaghetti' required if each set of points had its own set of wires.

The lead photo shows my control box that supports five sets of points in my layout, while Photo 1 shows the actual layout from above. The layout has two loops, each with a siding, plus a station at the centre.

Two of the sets of points allow trains to move from one loop to the other or back, while the other three allow trains to move between one of the loops and the sidings/station.

There are two LEDs and a toggle switch on the control box for each set of points. The green LEDs show the current direction of the points, while the toggle switch allows that to be changed.

The most common way to change the points on a model railway layout is to use a points motor. The insides of a typical one are shown in Fig.1.

If the motor is at position X and we apply 18V to the electromagnet windings between points A & B, the magnetic field attracts the iron arm, moving the sliding bar to the right (position Y).

If we then apply 18V to the winding

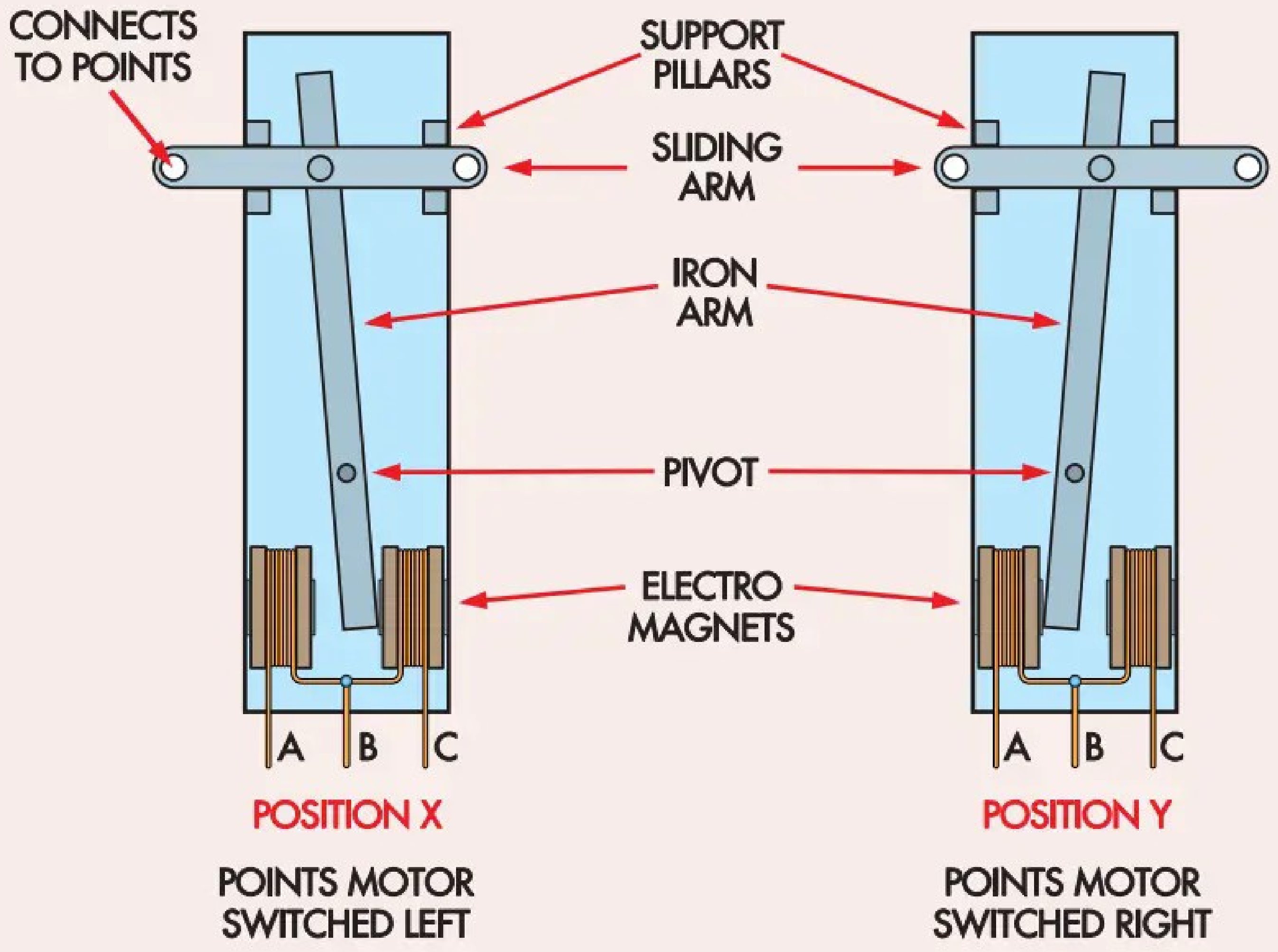

CONNECTS TO POINTS
SUPPORT PILLARS
SLIDING ARM
IRON ARM
PIVOT
ELECTRO MAGNETS
A B C
A B C
POSITION X
POINTS MOTOR SWITCHED LEFT
POSITION Y
POINTS MOTOR SWITCHED RIGHT

Fig.1: the basic configuration of a points motor. Depending on which side of the electromagnet is activated, the lever moves the points to one side or the other.

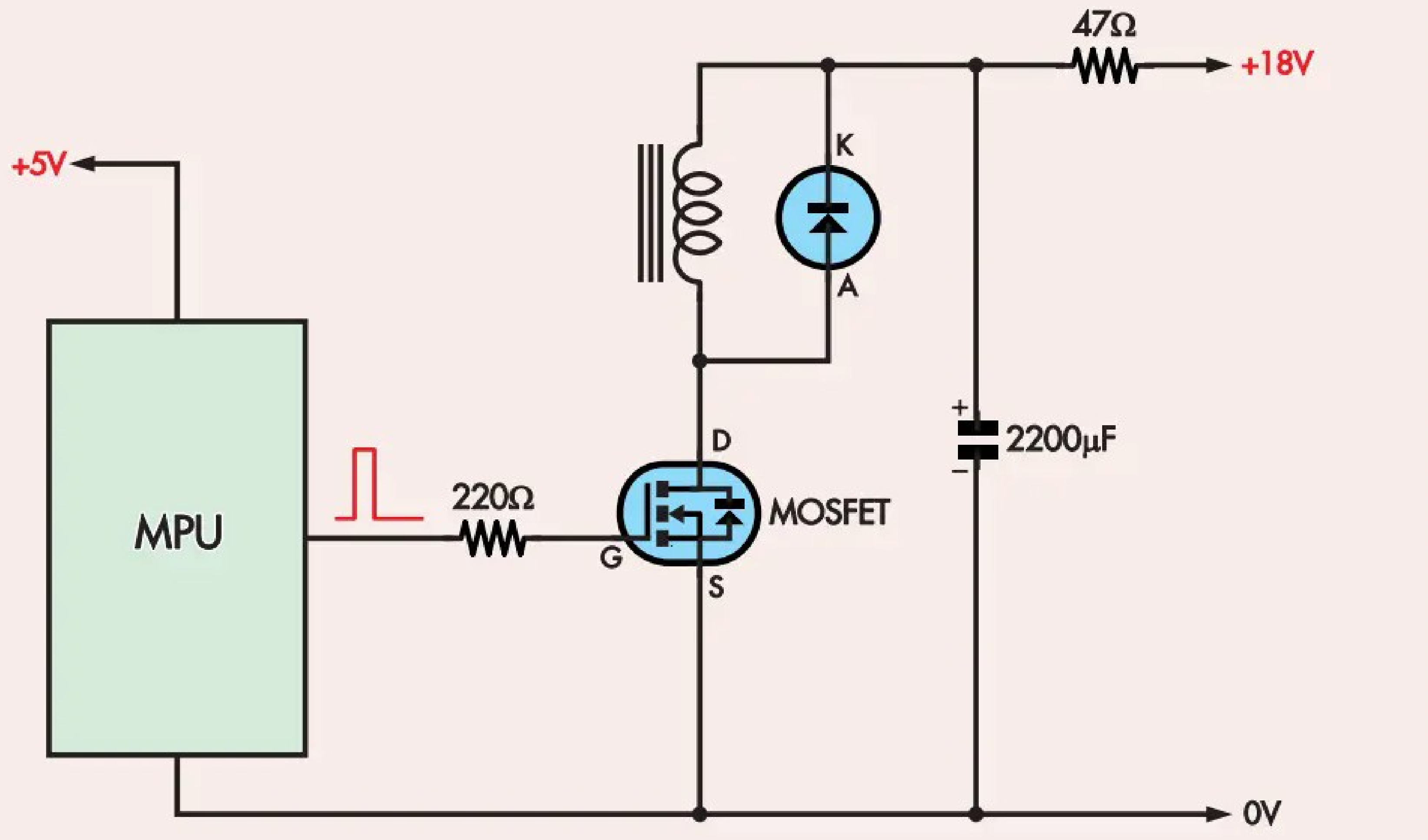

47Ω
+18V
+5V
K
A
MPU
220Ω
D
G
S
MOSFET
2200µF
0V

Fig.2: this basic circuit can switch a set of points in one direction. The Mosfet is pulsed to deliver enough current to switch it over, but not for so long that the coil burns out. Another Mosfet and diode is needed to provide switching in both directions.

between B & C, the points change back to their original position.

The windings produce a strong magnetic field and are made of heavy-gauge wire, having a typical resistance of 4Ω. If we had a constant 18V across them, we would have a steady current of 4.5A, which would soon burn out the coil. So we need a means of applying the current for no more than 200ms.

The second concern is the power supply's ability to deliver that much instantaneous power and current. That can be done using a circuit like the one shown in Fig.2. One end of the electromagnet coil is connected to the Mosfet drain while the other end connects to a 2200µF capacitor that is charged to 18V via a 47Ω resistor.

The Mosfet acts like a switch that is off when the gate voltage is 0V. If the gate voltage is brought to +5V for 200ms, the capacitor discharges most of its energy into the electromagnet, producing a strong magnet field and a loud click as the points change.

When the Mosfet switches off, the capacitor charges to approximately 18V in about 400ms, preparing it for the next pulse. A second Mosfet (not shown) is connected to the other end of the coil to switch the points back. They can share a single capacitor that's connected to the centre tap.

As mentioned earlier, this design's serial loop means you only need four wires from the control box for all the points. These are +18V, +5V, serial data and 0V. I ran a four-core alarm cable around my layout.

Scope 1 shows this in action (see page 43). The cyan trace is the Mosfet gate voltage, which is high for 200ms, while the yellow trace is the voltage between the Mosfet drain and ground. You can see how the capacitor recharges over a second or so following the points motor activation.

Block diagram Fig.3 shows how the modules are connected. One Receiver PCB is used for each set of points, with a single 'Transmitter' controlling up to eight sets (it transmits over a wire, not wirelessly). Each Receiver PCB has outputs to connect to the points motor and operate the associated signal (see Photo 2).

Each Receiver is given a unique address (0-7) with the combination of three jumpers. An additional

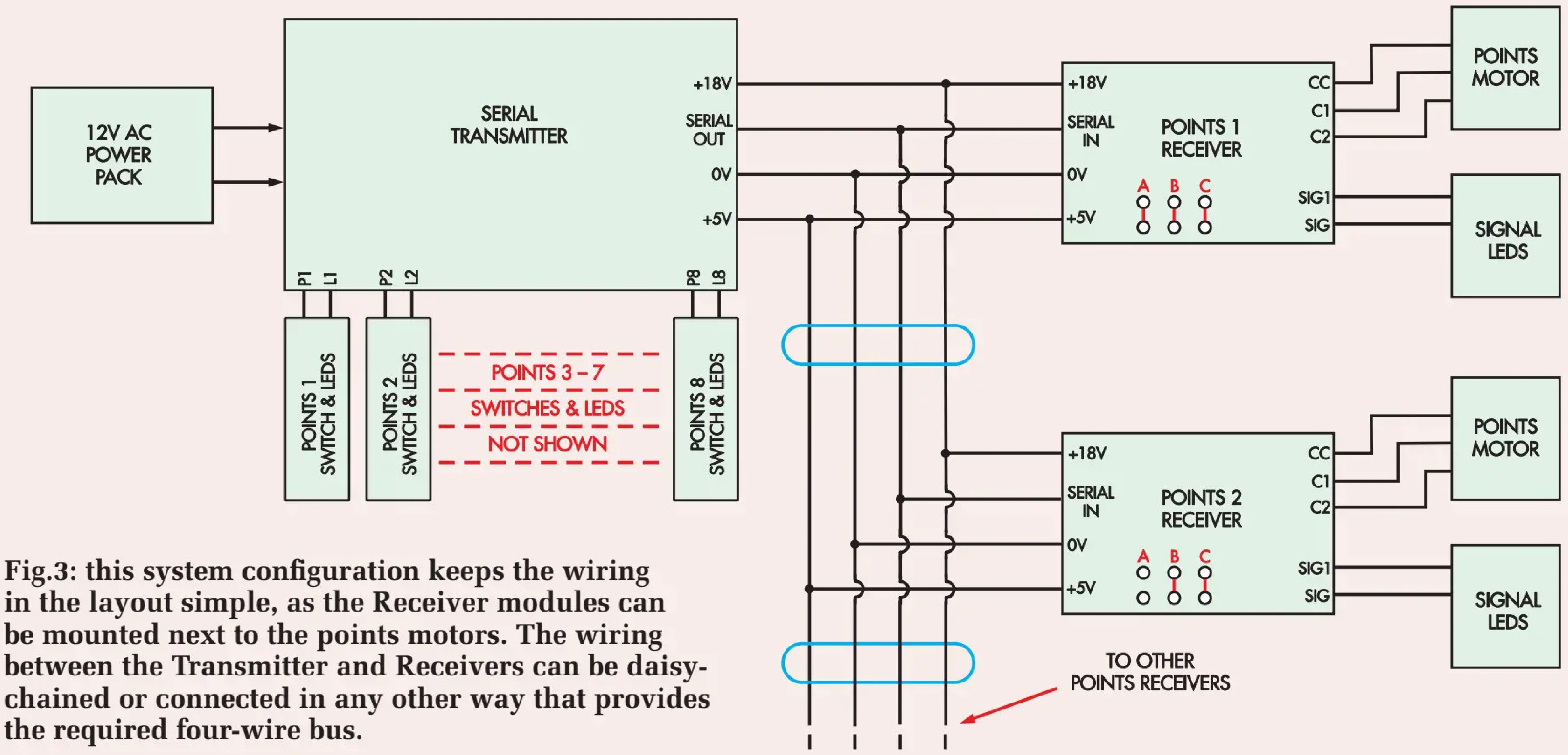

12V AC POWER PACK
SERIAL TRANSMITTER
+18V
SERIAL OUT
0V
+5V
P1
L1
P2
L2
P8
L8
POINTS 1 SWITCH & LEDS
POINTS 2 SWITCH & LEDS
POINTS 3 – 7 SWITCHES & LEDS NOT SHOWN
POINTS 8 SWITCH & LEDS
+18V
SERIAL IN
0V
+5V
POINTS 1 RECEIVER
A B C
CC
C1
C2
SIG1
SIG
POINTS MOTOR
SIGNAL LEDS
+18V
SERIAL IN
0V
+5V
POINTS 2 RECEIVER
A B C
CC
C1
C2
SIG1
SIG
POINTS MOTOR
SIGNAL LEDS
TO OTHER POINTS RECEIVERS

Fig.3: this system configuration keeps the wiring in the layout simple, as the Receiver modules can be mounted next to the points motors. The wiring between the Transmitter and Receivers can be daisy-chained or connected in any other way that provides the required four-wire bus.

Transmitter can be used if you need more than eight sets of points. The Transmitter is housed in the control box, with power for all the modules provided by a 12V AC 1A plugpack. If you have 12V AC available from a different source, you could use that instead.

The complete system comprises the PCBs mentioned above, the points and motors, signals, control box wiring and layout wiring.

Circuit details

The circuit of the Transmitter (control box) is shown in Fig.4. Up to eight switches and sets of LEDs are wired to microcontroller IC1. Eight of its digital input pins (RA0, RC0-RC4, RA4 & RA5) are used to sense the positions of the points control switches. Each input has a 10kΩ pull-up, so either the switch pulls that input to GND or the resistor pulls it up to +5V.

The same switch poles light one of the two connected green LEDs by pulling one of the cathodes to GND. The anodes are connected to a common 680Ω resistor to +5V.

IC1 constantly checks the states of the eight switches and delivers a continuous serial stream at its RC5 digital output. That is fed to the eight 'Receivers' via a 1kΩ resistor, so they know which state the points need to be in. The 1kΩ series resistor protects the microprocessor from damage if the serial line is accidentally shorted to ground.

For the power supply, the incoming 12V AC is applied to a bridge rectifier with a 2200µF smoothing capacitor to get around 18V DC. This depends on the transformer regulation and can range between 16V and 18V DC; 16V is sufficient to operate the points motor. That voltage is fed to the points motors and the input of linear regulator REG1, which produces the 5V DC supply for IC1 and the microcontrollers in up to eight connected Receivers.

The 1000µF capacitor smooths out any ripple that makes its way through the 7805 regulator, while the 100nF capacitors reduce high-frequency transients from the supply and ensure stability in the linear regulator.

Fig.5 shows the circuit of one Receiver. The serial data from the Transmitter goes to the RC0 digital input of IC2, which is powered by the 5V rail produced by the Transmitter. It

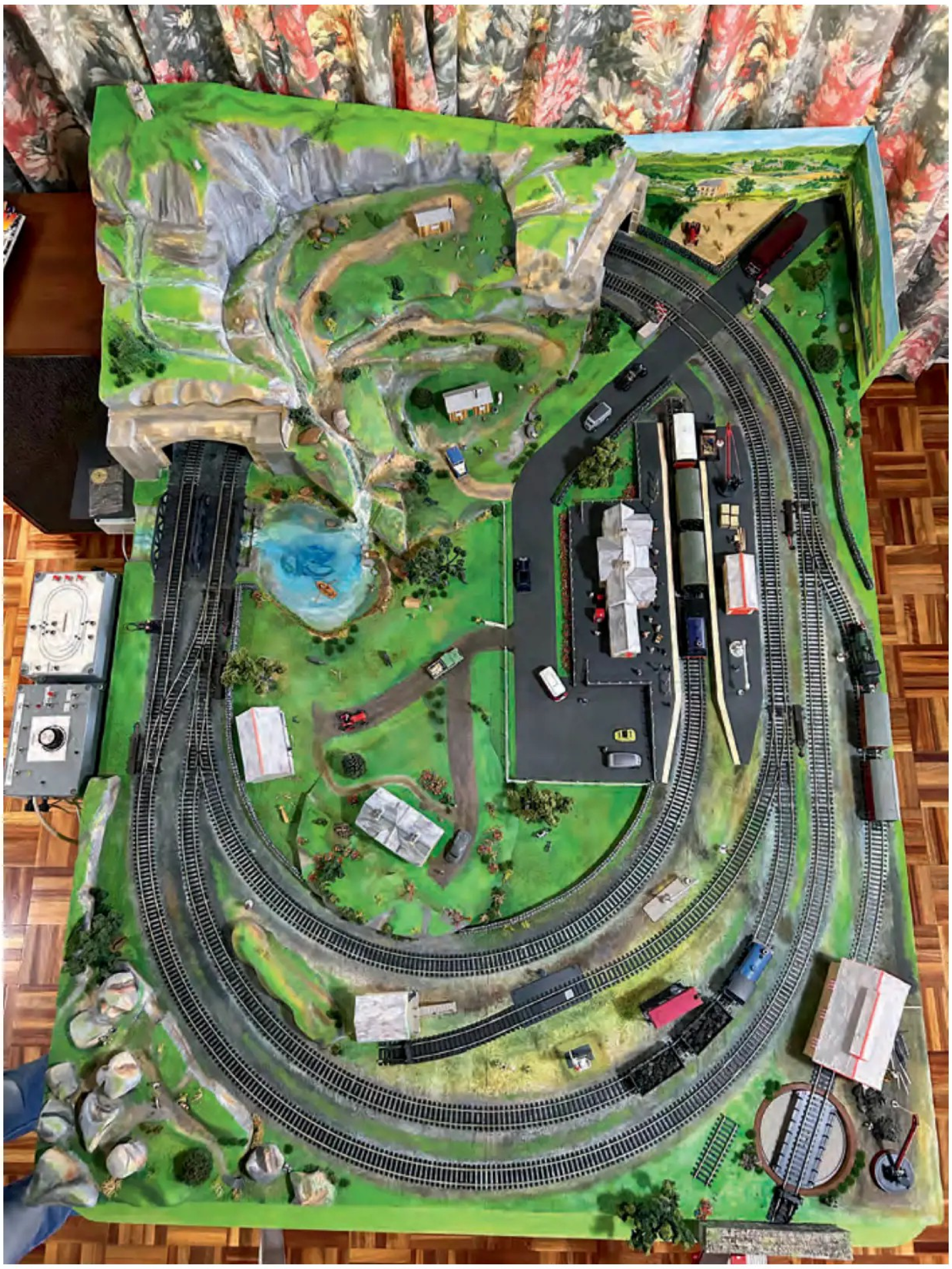
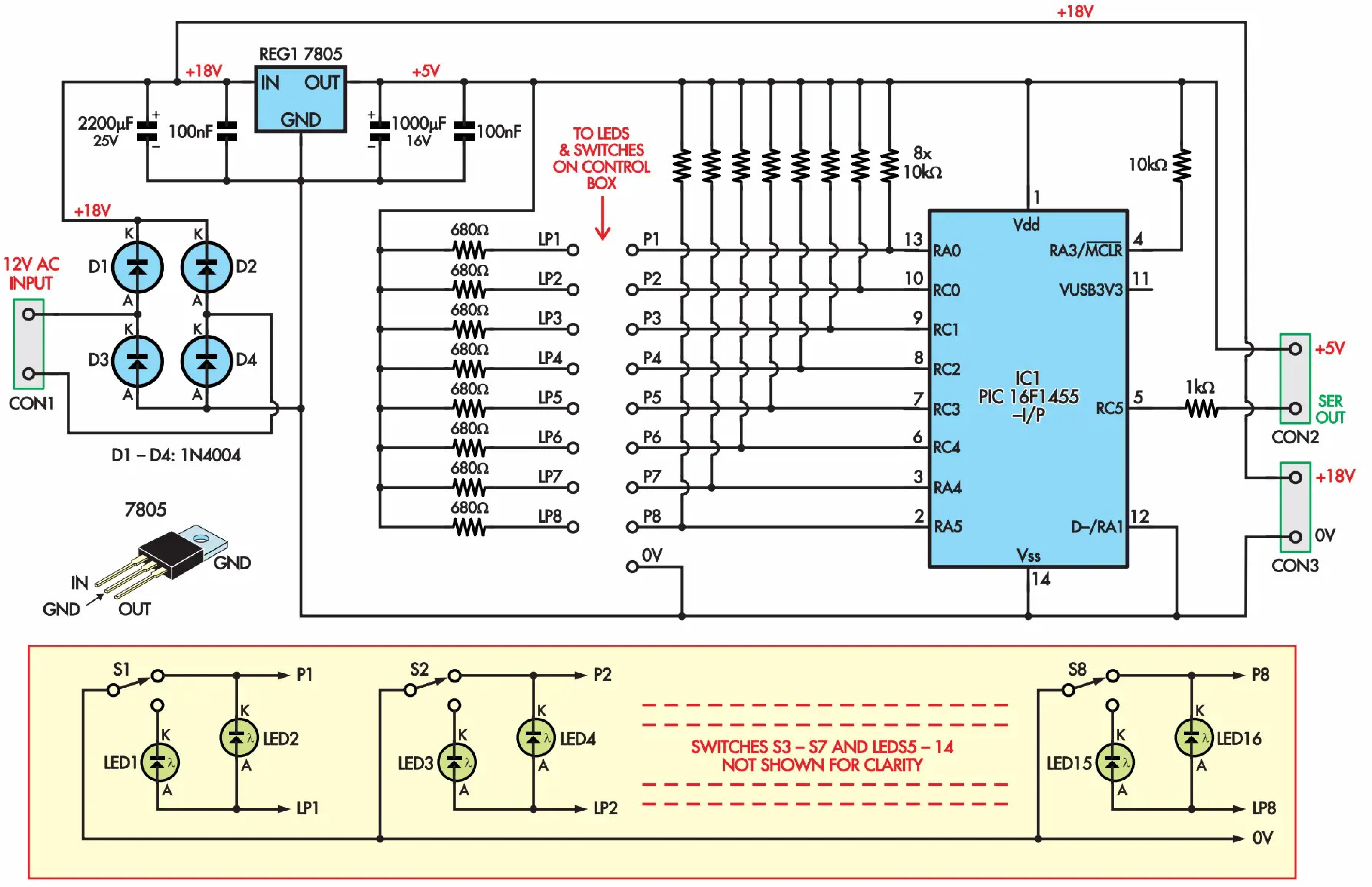
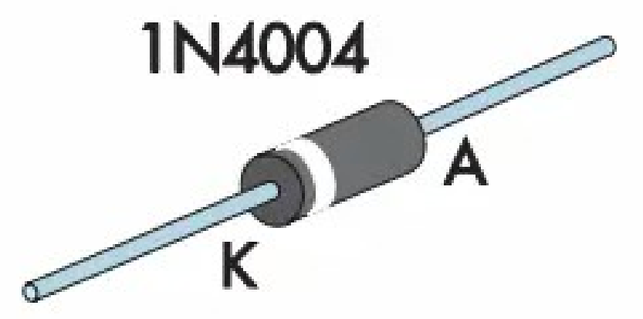


Photo 1 (above): a view of my layout from above. You can see how it corresponds to the diagram and controls shown in the lead photo.

Photo 2 (left): a close-up of one of the signals I designed to accompany the points. They can be made using a lathe and a few bits of metal you can get from hobby shops.

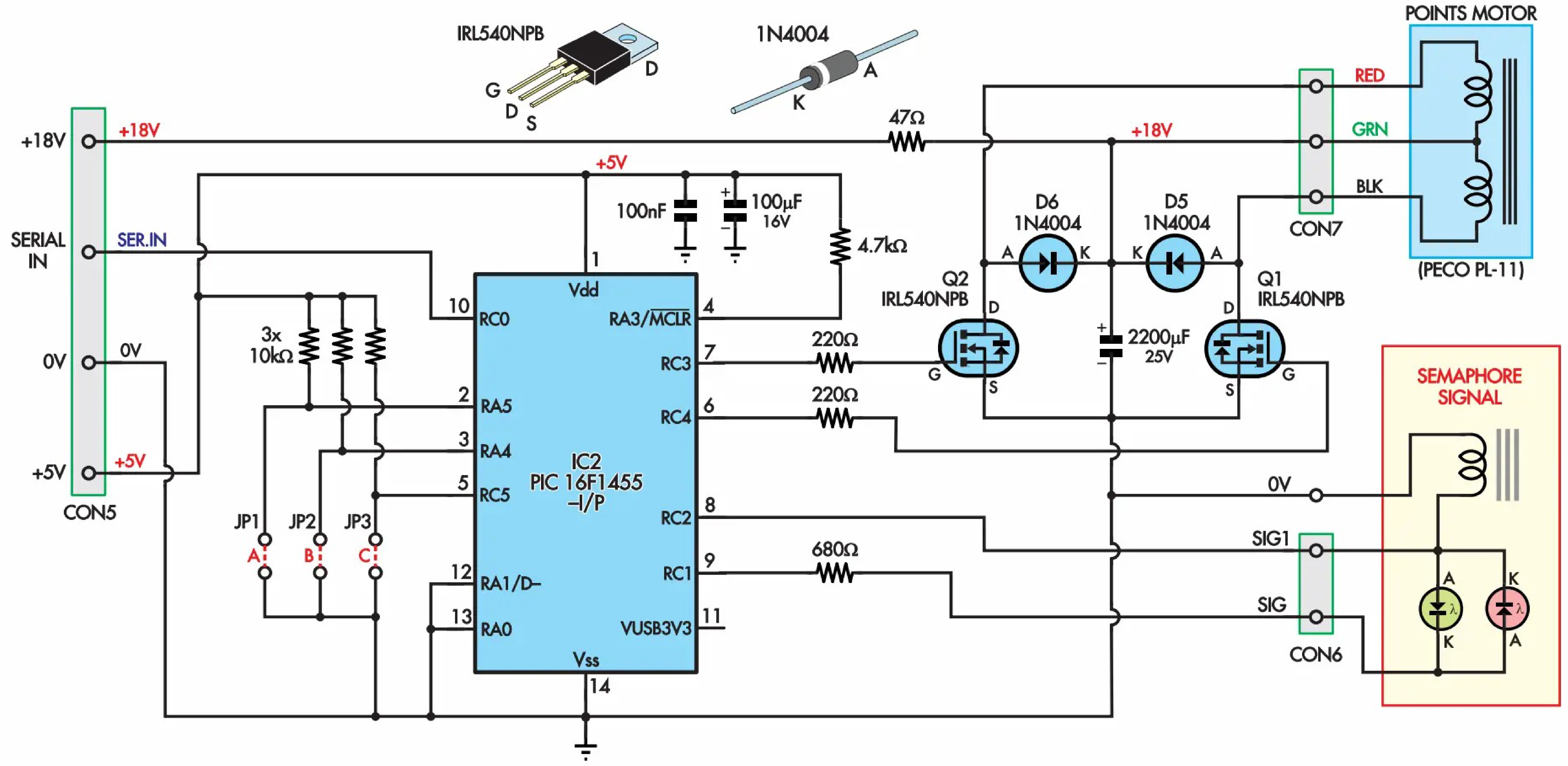

+18V
REG1 7805
IN
OUT
GND
+18V
+5V
2200µF 25V
100nF
1000µF 16V
100nF
TO LEDS & SWITCHES ON CONTROL BOX
8x 10kΩ
10kΩ
12V AC INPUT
CON1
D1
D2
D3
D4
K
A
D1 – D4: 1N4004
7805
GND
IN
GND
OUT
680Ω
LP1
LP2
LP3
LP4
LP5
LP6
LP7
LP8
P1
P2
P3
P4
P5
P6
P7
P8
0V
IC1
PIC 16F1455 –I/P
Vdd
RA0
RC0
RC1
RC2
RC3
RC4
RA4
RA5
RA3/MCLR
VUSB3V3
RC5
D–/RA1
Vss
1kΩ
+5V
SER OUT
CON2
+18V
0V
CON3
S1
S2
S8
LED1
LED2
LED3
LED4
LED15
LED16
SWITCHES S3 – S7 AND LEDS5 – 14 NOT SHOWN FOR CLARITY

(SWITCHES AND LEDS ARE MOUNTED ON THE CONTROL BOX)



MODEL RAILWAY POINTS CONTROLLER TRANSMITTER CIRCUIT

Fig.4: the Transmitter circuit consists of a microcontroller, IC8, connected to up to eight toggle switches and eight pairs of LEDs. It encodes the switch positions into a serial stream at its pin 5 digital output that's fed to the Receivers so they can actuate the points appropriately.


IRL540NPB
G
D
S
D
1N4004
A
K
POINTS MOTOR
RED
GRN
BLK
CON7
(PECO PL-11)
+18V
+18V
SERIAL IN
SER.IN
0V
0V
+5V
+5V
CON5
47Ω
+5V
100nF
100µF 16V
4.7kΩ
+18V
D6 1N4004
D5 1N4004
Q2 IRL540NPB
Q1 IRL540NPB
2200µF 25V
3x 10kΩ
IC2
PIC 16F1455 –I/P
Vdd
RC0
RA5
RA4
RC5
RA1/D–
RA0
RA3/MCLR
RC3
RC4
RC2
RC1
VUSB3V3
Vss
220Ω
220Ω
680Ω
JP1
JP2
JP3
A
B
C
0V
SIG1
SIG
CON6
SEMAPHORE SIGNAL

MODEL RAILWAY POINTS CONTROLLER RECEIVER CIRCUIT

Fig.5: microcontroller IC2 in the Receiver decodes the serial stream and, based on its identity set by jumpers JP1-JP3, extracts the appropriate command signals and drives Mosfets Q1 & Q2 to control the points motor. It also updates the state of the signal/semaphore when the points change.

decodes the serial stream and ignores everything except the points position that matches its identity, 0-7, depending on the settings of jumpers JP1-JP3.

Those jumpers connect to the RA5, RA4 & RC5 digital inputs of IC2. If a jumper is inserted, shorting the two header pins, it pulls the connected pin low. Otherwise, that pin is pulled high by a 10kΩ resistor. That means they are all at a high logic level unless a jumper shunt is added. Table 1 shows the jumper setting for each of the eight channels.

When the desired points position changes, it brings one of the RC3 & RC4 digital outputs high for 200ms to drive the points motor as described earlier. It also updates the states of digital outputs RC1 & RC2 to light the appropriate LED in the signal, or change the state of the optional Semaphore with its signal input connected to SIG1 and its GND to 0V.

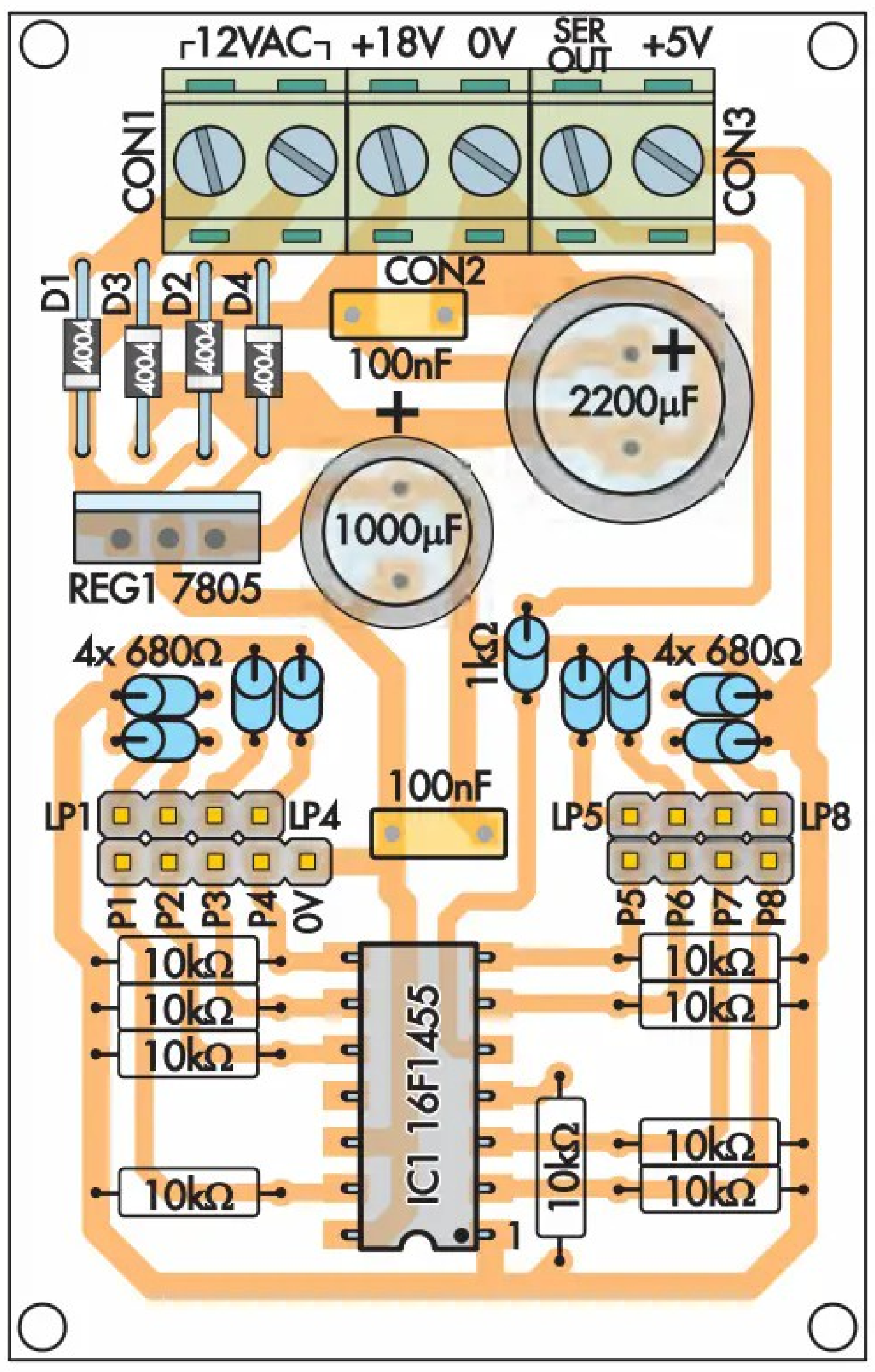
Diodes D5 & D6 are provided because when Q1 or Q2 switches off, the magnetic field in the motor windings will collapse and cause a voltage spike at the drain of the Mosfet that was on. These diodes clamp the voltage, preventing damage to the Mosfets.

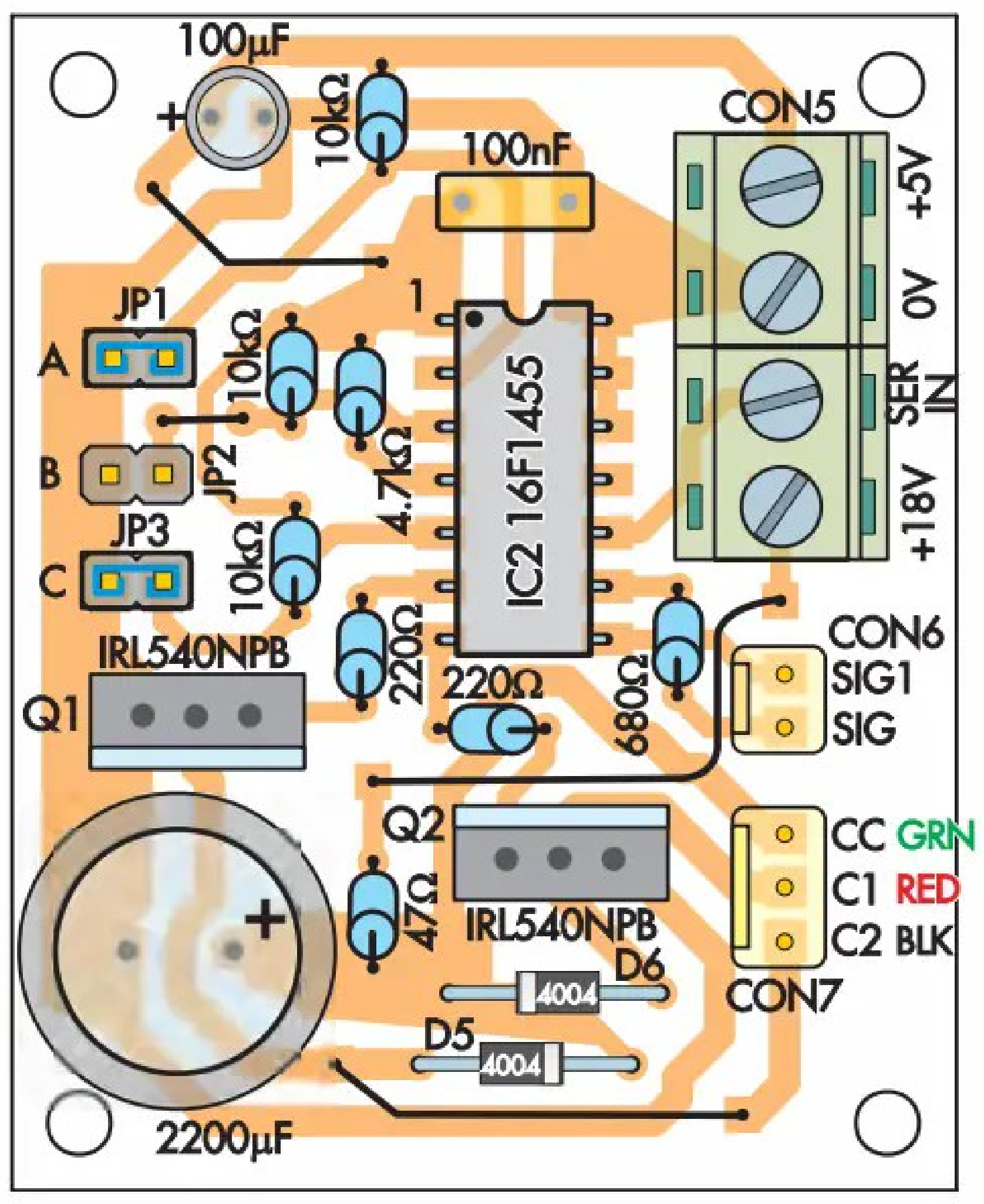
The 100µF and 100nF supply bypass capacitors in each Receiver are necessary since the Transmitter that's the source of the 5V rail could be some distance away, connected by relatively thin wires, so the supply needs local filtering.

Transmitter construction

The Transmitter is built on a 74 × 47mm single-sided PCB coded 09101241 – see the overlay diagram, Fig.6. The power supply connections and four wires that go to the Receivers connect via the terminal blocks at the top of the PCB. In contrast, the off-board switches and LEDs are connected via the headers near the middle of the board. Photo 3 shows the assembled board.

Fig.6: assembly of the Transmitter PCB is straightforward. The power supply inputs are at upper left, the four serial/power bus connections are at upper right, and the headers to connect up to eight toggle switches and indicator LEDs are in the middle. ▼





▲

Fig.7: if using our commercially-produced Receiver PCBs, there's no need to fit the four wire links shown here. Ensure the four bus terminals connect to the corresponding terminals on the Transmitter PCB.

Start by fitting the resistors immediately on either side of IC1, followed by the IC socket with the notched end at the bottom. You can then solder the header pins, made from strips four or five pins long that can be snapped from longer headers.

Follow with the capacitors, taking care with the orientation of the electrolytics (the longer lead is positive while the striped side of the can is negative).

Don't solder the PIC directly to the PCB, as there is no provision for in-circuit programming.

Next, add the remaining resistors, which are mounted vertically, then dovetail the three terminal blocks and solder the whole lot at the top of the PCB, with the wire entries towards that edge.

Solder in the 7805 voltage regulator and the 1N4004 diodes as per the layout diagram, taking care to match their orientations with what's shown in those figures.

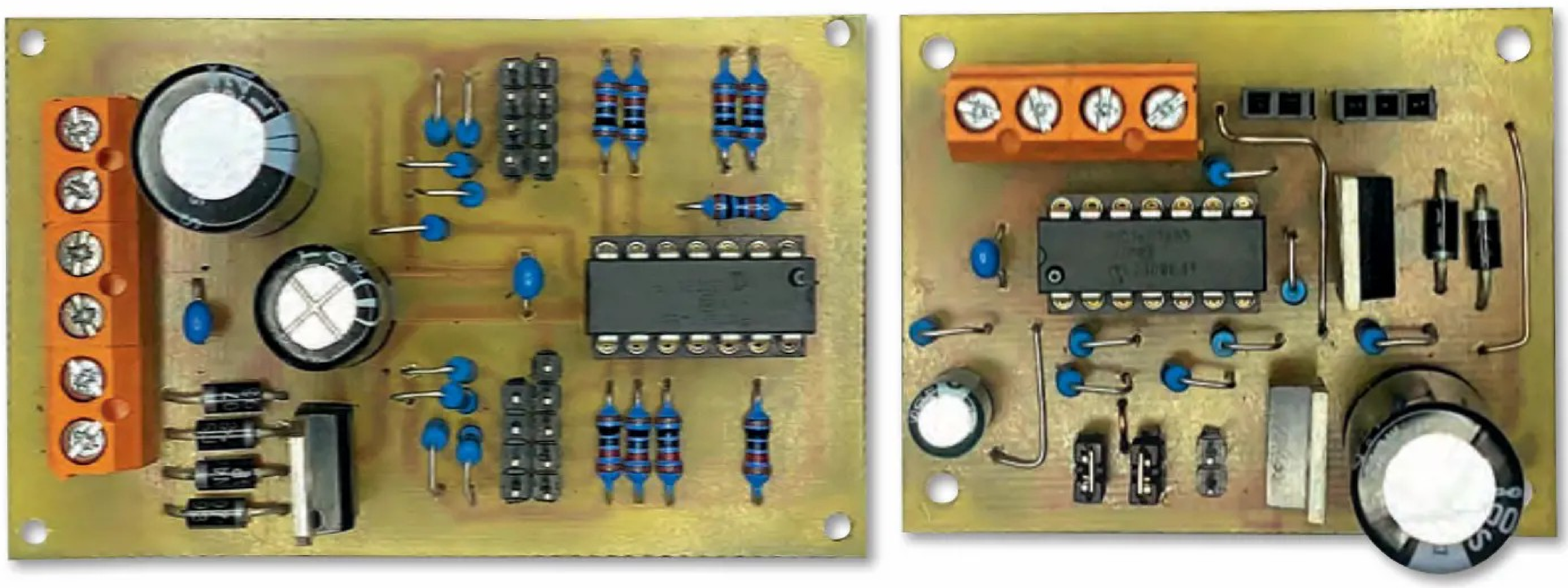
If you have purchased the PIC16F1455 microcontroller from the Silicon Chip online shop, it will already have the firmware loaded. If you wish to do this yourself, the files can be downloaded from **siliconchip.au/Shop/6/276**

Check for dry joints and solder bridges and rectify them if you find any. You can then plug the header sockets onto the header pins, ready to solder the wires to the LEDs and switches. If you don't have individual 4-pin & 5-pin strips, you can cut up longer strips with a hacksaw or side cutters.

Receiver assembly

The Receiver is built on a 56 × 45mm single-sided or double-sided PCB coded 09101242 – see the overlay diagram, Fig.7. The PCBs we supply will be double-sided, so they won't need the four wire links.

If you have single-sided boards (eg, you made them yourself), start by fitting the four wires shown in Fig.7. It



Photos 3 & 4: the left-hand photo is the Transmitter PCB. Commercial PCBs will have silkscreened labelling. Note the headers for connecting the switches and LEDs; the extra pin is the 0V (GND) connection. The right-hand photo is the Receiver PCB. As commercially-made PCBs will have two layers, you won't have to fit the links, saving some time.

is advisable to use solid-core insulated wire (‘Bell wire’). You can see from Photo 4 that I used tinned copper wire; if doing the same, be careful to route the wires so they can’t short against anything.

The construction procedure is the same as for the Transmitter, although all the resistors are mounted vertically on this board. Watch the orientations of all diodes, Mosfets, electrolytic capacitors and the IC socket. Also check that the terminal block wire entries are facing the nearest edge of the board.

You will see that I used pieces of socket strip for CON6 & CON7, although I have specified polarised headers and matching plugs in the parts list. The advantage of the latter is that you can’t accidentally connect the points or signal backwards if you unplug and replug them later.

While IC2 is the same type of chip as IC1 (a PIC16F1455), it is programmed differently, so make sure you get the right ones when purchasing preprogrammed chips. Similarly, if programming them yourself, use the HEX file ending in B for the Receiver chips and the -A file for the Transmitter chip.

Check for dry joints and solder bridges, then refer to Table 1 to see which jumpers you need to plug into the headers for each Receiver based on its number. Photo 4 shows the jumper settings for points #5.

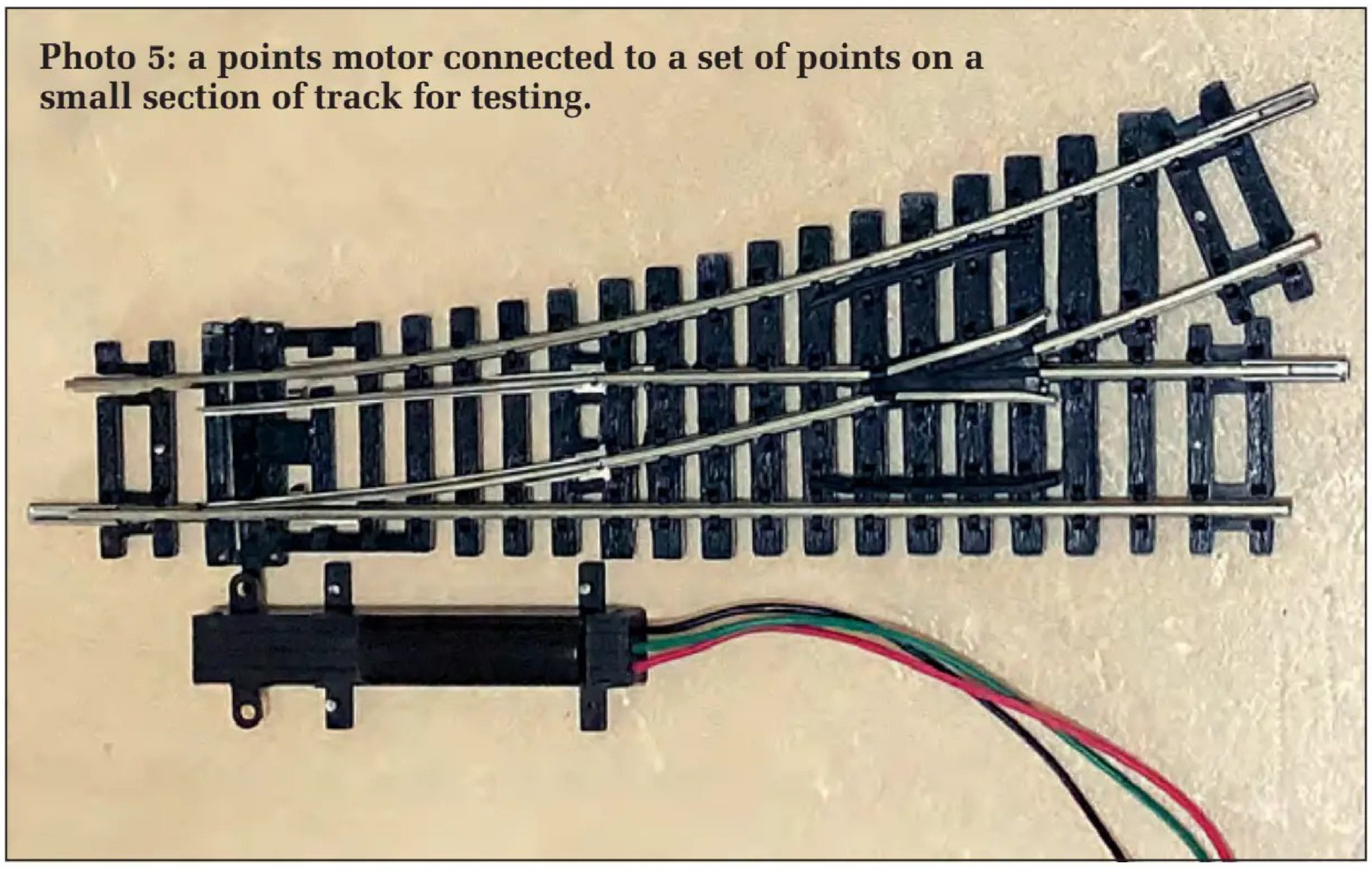


Photo 5: a points motor connected to a set of points on a small section of track for testing.

Making the signals

You don’t strictly need the signals, but they improve the appearance and realism of the layout. Fig.8 shows how I made them. The mounting pole is made from a length of ³⁄₃₂in (~2.38mm) square hollow brass tube. Cut it to size and clean up the ends using a file.

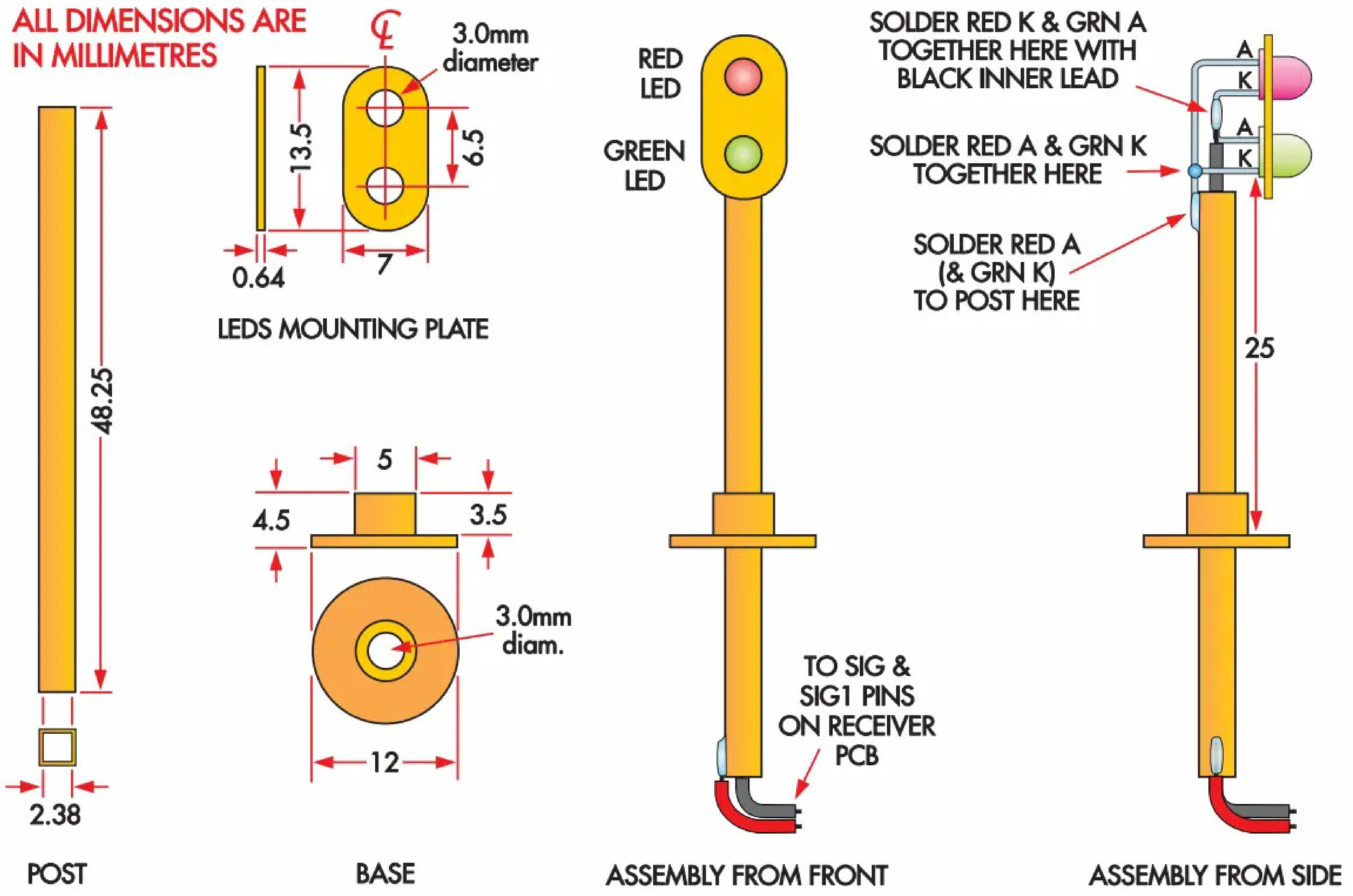

ALL DIMENSIONS ARE IN MILLIMETRES
℄
3.0mm diameter
13.5
6.5
0.64
7
LEDS MOUNTING PLATE
48.25
5
4.5
3.5
3.0mm diam.
12
2.38
POST
BASE
RED LED
GREEN LED
TO SIG & SIG1 PINS ON RECEIVER PCB
ASSEMBLY FROM FRONT
SOLDER RED K & GRN A TOGETHER HERE WITH BLACK INNER LEAD
A
K
A
K
SOLDER RED A & GRN K TOGETHER HERE
SOLDER RED A (& GRN K) TO POST HERE
25
ASSEMBLY FROM SIDE

Fig.8: here are the details of the parts used to make the optional signal to go with each set of points. You could use the Semaphore described in the April 2022 issue instead.

The LED mounting plate is made from a piece of 0.05in thick by 0.5in wide (1.3 × 12.7mm) brass strip. Drill the 3mm diameter holes 6.5mm apart, then cut the plate to length. Use a linisher or file to round the ends to size and clean up the edges, then paint the plate matte black.

For the base, place a piece of 20mm aluminium round rod into a three-jaw chuck so that 10mm protrudes. Face the end and turn it down to a 5mm diameter for a length of 3.5mm. Using a centre drill, followed by a 3mm drill, bore out the hole to a depth of 5mm. Part it off to a length of 4.5mm.

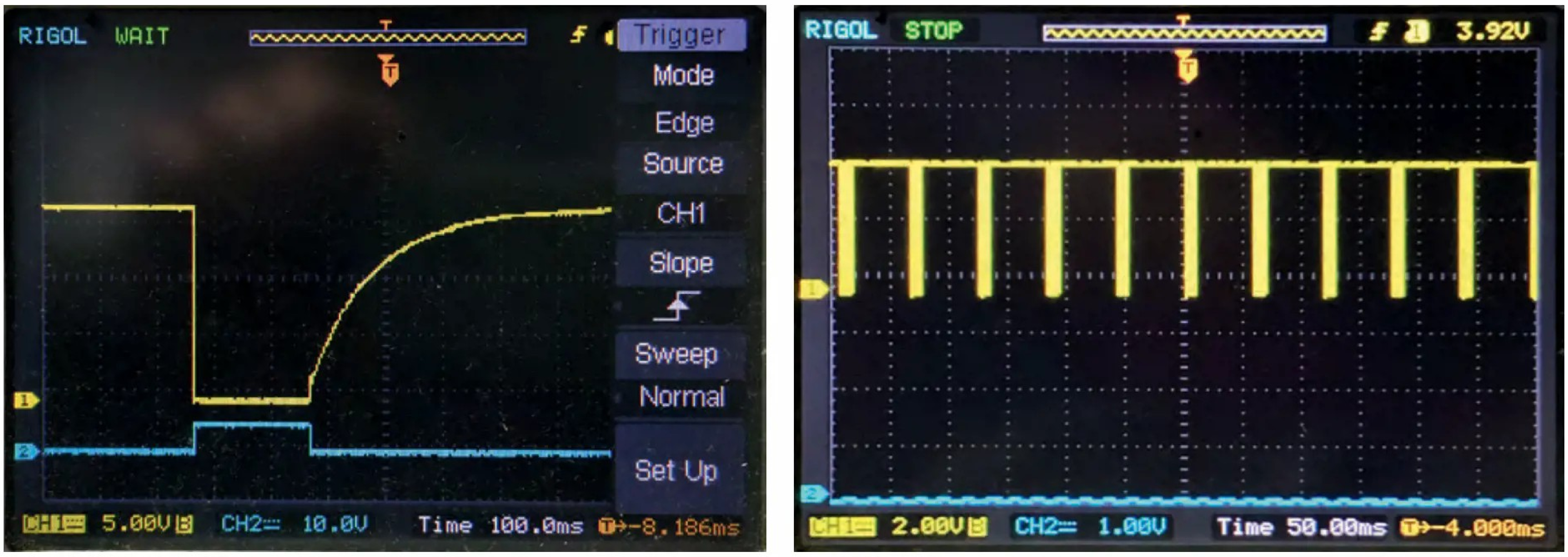
Fit 3mm red and green LEDs into the LED mounting plate, noting the orientation shown on the drawing. Bend, cut and solder the leads as shown to create the LED assembly. They are soldered anode-to-cathode, in inverse parallel.

The LED assembly is then soldered to the post. Clean, tin and flux the mating surfaces between the LED assembly and the post. Use a soldering iron to heat the assembly until you see solder coming out of the joint. File off any excess solder. Slide the base onto the post and lock it in place 25mm from the green LED lead using Loctite GO2 (or equivalent).

To get power to the LEDs, take two 300mm lengths of thin hookup wire (red & black). You can strip these out of an old USB cable. Remove about 2mm of the insulation on both ends and tin the exposed wire. Clean and tin the bottom edge of the post, then place the red wire on top and solder it to the post.

Thread the black wire up the centre of the post and connect it to the LEDs, as shown in Fig.8. Attach header pins to the other end of the red and black wires, and cover the wire connections with heatshrink tubing.

Cover the LED assembly with masking tape and spray the rest with silver paint. Finally, test the signal by connecting a 680Ω resistor in series with the positive lead of a 5V DC power supply. Connect the other end of the 680Ω resistor to the signal red lead and the black lead to the supply's negative. The red LED should



Scope 1 (left): the Mosfet gate drive (cyan) and drain voltage (yellow) when driving one side of a points motor. After switching the points, the capacitor takes about 400ms to recover its charge.

Scope 2 (right): if the Transmitter is operating correctly, the serial waveform from pin 5 of IC1 should look like this.

glow. Reverse the connections, and the green LED will light.

Mounting the signal

If your layout is on a timber base, drill a 3mm hole at a suitable location near the entry to the points. Insert the signal wire end into the hole first, until the base is flush with the board. Glue it in place using Loctite GO2.

My layout is on a polyurethane base, so I did the same but used a 2mm drill. I enlarged the hole to 3mm from the underside with about 24mm of the hole length remaining at 2mm. Wait till you have tested the PCBs before securing the signals in place.

Preparing for testing

Before testing the Transmitter and Receiver PCBs, make a temporary set of points with a points motor attached, as shown in Photo 5. I mounted it on a scrap piece of 30mm polystyrene. Firstly, mount the points using 0.78 × 25mm pins.

Using the points operation lever, move the points in the direction shown in the photo. Take a points motor and orientate it with its actuator down. Place the hole in the actuator directly over the pin in the point's operation lever and pin the motor in place. Switch the points manually, checking that the point motor's actuator moves smoothly in and out.

Prepare the wires on the points motor to connect to a Receiver PCB. If using the specified polarised headers, that means crimping and/or soldering them into the header plug pins, then pushing those pins into the moulded plastic block in the correct order to mate with the header on the Receiver.

I soldered the wires to header pins to match the sockets I soldered to the board, and covered the solder joints with heatshrink tubing.

Transmitter testing

Check the orientation of the capacitors, diodes, and the voltage regulator, then apply 12V AC to the screw terminals as shown in Fig.6 (the two at upper left). Use a DVM to check that you have +5V and between 16-18V referenced to 0V on the terminal blocks. With the DVM black lead connected to pin 14 and the red lead to pin 1 of IC1's socket, check that you measure +5V DC.

Remove power and plug in the PIC16F1455, being careful to avoid folding its legs. Reconnect the supply and, if you have an oscilloscope, check to see that serial data is being sent out from the serial screw terminal, as shown in Scope 2. Otherwise, you can use a frequency counter to check for activity.

The next step is to connect the Transmitter to a Receiver but, before doing so, recheck the Receiver board to verify that the diodes, Mosfets, capacitors and IC2 are correctly orientated.

Connect the points assembly, Transmitter and Receiver as shown in Fig.9. Set the jumper links for points 1 (see Table 1). Apply 12V AC to the Transmitter, and you should see the green signal LED light and the points motor switch to the left. Short pin 13 of IC1 to ground (pin 14 is ground); the red signal LED should light, and the points motor should switch to the right.

Switch off the power and change the jumper settings to #2. Switching the power on will again cause the signal

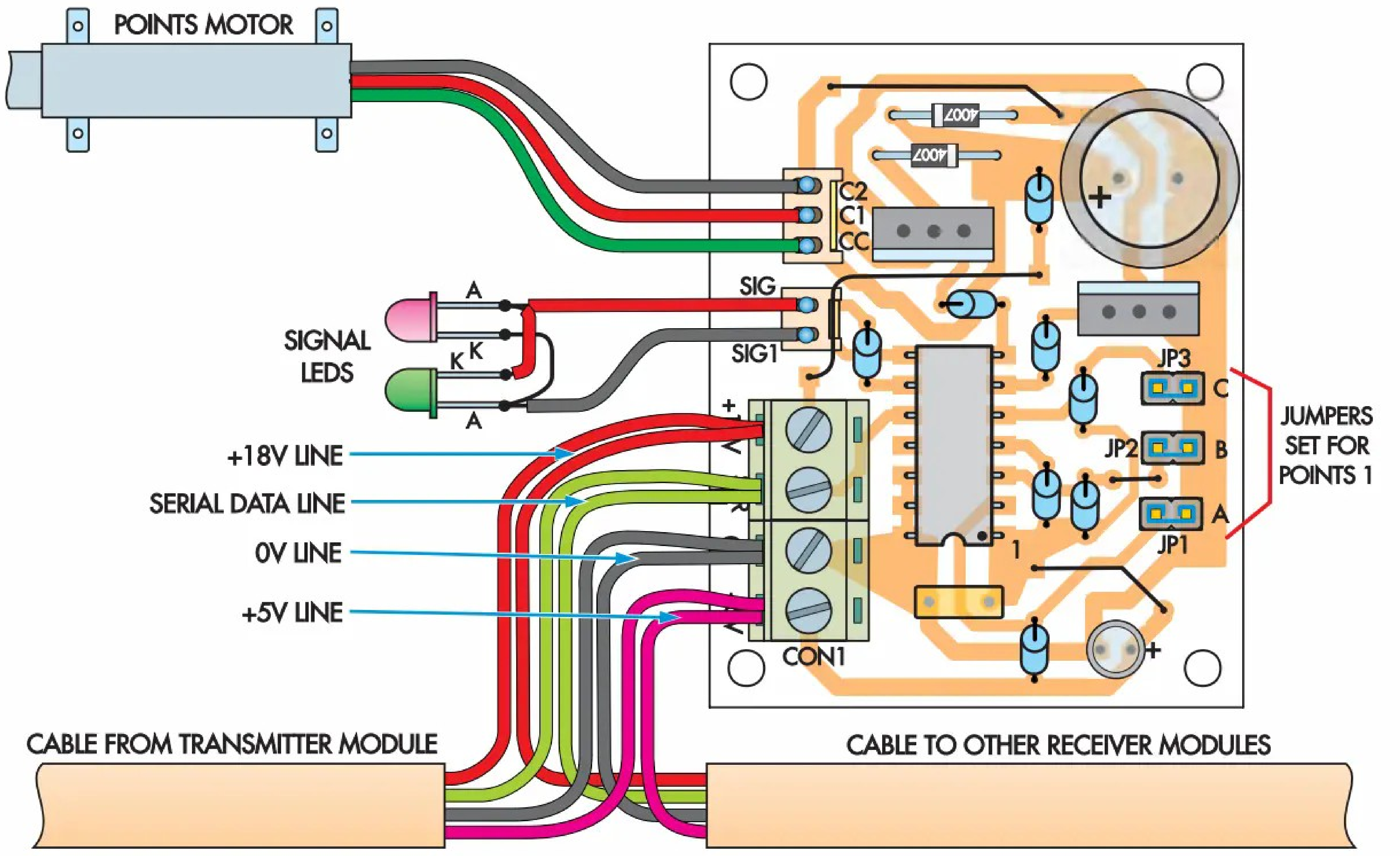


Fig.9: the wiring for the first set of points. It's the same for the other seven sets of points, except that the three jumper settings change (see Table 1 below).

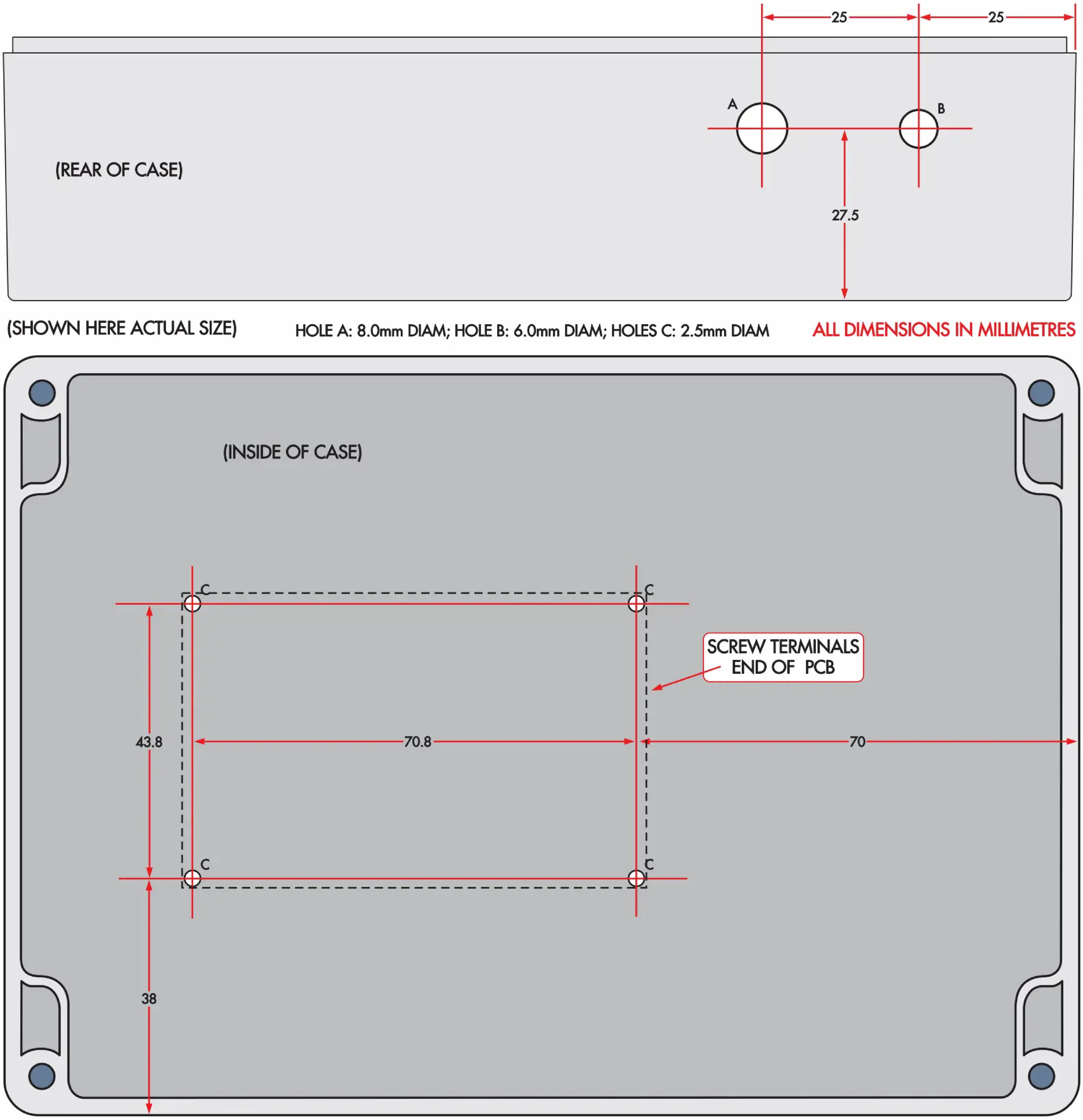

25
25
A
B
(REAR OF CASE)
27.5
(SHOWN HERE ACTUAL SIZE)
HOLE A: 8.0mm DIAM; HOLE B: 6.0mm DIAM; HOLES C: 2.5mm DIAM
ALL DIMENSIONS IN MILLIMETRES
(INSIDE OF CASE)
C
C
C
C
SCREW TERMINALS END OF PCB
43.8
70.8
70
38

Fig.10: the suggested positions for the PCB mounting holes, power input socket and serial bus cable in the control box.

green LED to glow and the points motor to go to the left. This time, short pin 10 of IC1 to ground; the red signal LED will glow, and the points motor will move to the right. Repeat for the remaining point channels, referring to Table 1 and Fig.4.

When finished, set each Receiver to a different ID, referring to Table 1, and use a small label or marker pin to write the IDs you've assigned on the Receiver PCBs.

Finishing the control box

You will now need to create a suitable label for the control box. I did this on the computer, scaled it to size to fit the control box lid and printed it onto silver sticky decal paper. Remove the backing sheet and carefully fit the label to the box, avoiding any air bubbles under the surface.

As every layout is different, I haven't made a drawing of the drilling details of the lid. However, Fig.10 shows the drilling details for the base and sides of the box.

Drill out the holes for the green LEDs and switches, then fit them to the case. To connect the 12V AC plugpack, you need to drill a hole in the back of the box for the barrel connector, plus another for the four-wire serial cable exit.

The Transmitter PCB is mounted on the bottom of the box using M2.5 screws and nuts. Fig.11 shows the wiring for the first set of points, which connects to 0V, P1 and LP1. The other channels follow the same scheme; eg, for the second set of points, the wires connect to 0V, P2 and LP2.

These connections can be made by soldering the wire to the socket pin, covering the solder joint with a short

Parts List – Model Railway Points Controller

Transmitter

1 single-sided PCB coded 09101241, 74 × 47mm
1 flanged ABS plastic enclosure, 171 × 121 × 55mm [Gainta G313MF]
1 14-pin DIL IC socket (for IC1)
1-8 SPDT or DPDT toggle switches (S1-S8) (one per set of points)
3 2-way mini terminal blocks, 5/5.08mm pitch (CON1-CON3)
1 panel-mount barrel socket to suit plugpack (CON4)
3 4-pin headers
1 5-pin header
3 4-pin female header sockets
1 5-pin female header socket
4 M2.5 × 10mm panhead machine screws
8 M2.5 hex nuts
1 long four-core wire (to connect the Transmitter to all Receivers)
various lengths and colours of hookup wire
various lengths of heatshrink tubing
1 12V AC 1A plugpack

Semiconductors
1 PIC16F1455-I/P micro programmed with 0910124A.HEX, DIP-14 (IC1)
1 7805 5V 1A linear regulator, TO-220 (REG1)
2-16 3mm green LEDs (LED1-16; two per set of points)
4 1N4004 400V 1A diodes (D1-D4)

Capacitors
1 2200µF 25V low-ESR radial electrolytic
1 1000µF 16V low-ESR radial electrolytic (5mm lead pitch)
2 100nF 50V ceramic

Resistors *(all $\frac{1}{4}$W 1% axial)*
9 10kΩ   1 1kΩ   8 680Ω

Receiver (per set of points, 1-8 per Transmitter)

1 single-sided or double-sided PCB coded 09101242, 56 × 45mm
1 set of points
1 PECO PL-11 points motor
1 14-pin DIL IC socket (for IC2)
2 2-way mini terminal blocks, 5/5.08mm pitch (CON5)
1 2-pin polarised header with matching plug and pins (CON6)
1 3-pin polarised header with matching plug and pins (CON7)
3 2-pin headers (JP1-JP3)
0-3 jumper shunts (JP1-JP3; number required depends on Receiver ID)
various lengths and colours of hookup wire
various lengths of heatshrink tubing

Semiconductors
1 PIC16F1455-I/P micro programmed with 0910124B.HEX, DIP-14 (IC2)
2 IRL540N, MTP3055VL or IPP80N06S4L-07 N-channel logic-level Mosfet or similar, TO-220 (Q1, Q2)
2 1N4004 400V 1A diodes (D5, D6)

Capacitors
1 2200µF 25V low-ESR radial electrolytic
1 100µF 16V low-ESR radial electrolytic (2-2.54mm lead pitch)
1 100nF 50V ceramic

Resistors *(all $\frac{1}{4}$W 1% axial)*
3 10kΩ   1 4.7kΩ   1 680Ω   2 220Ω   1 47Ω

Signal (per optional signal)

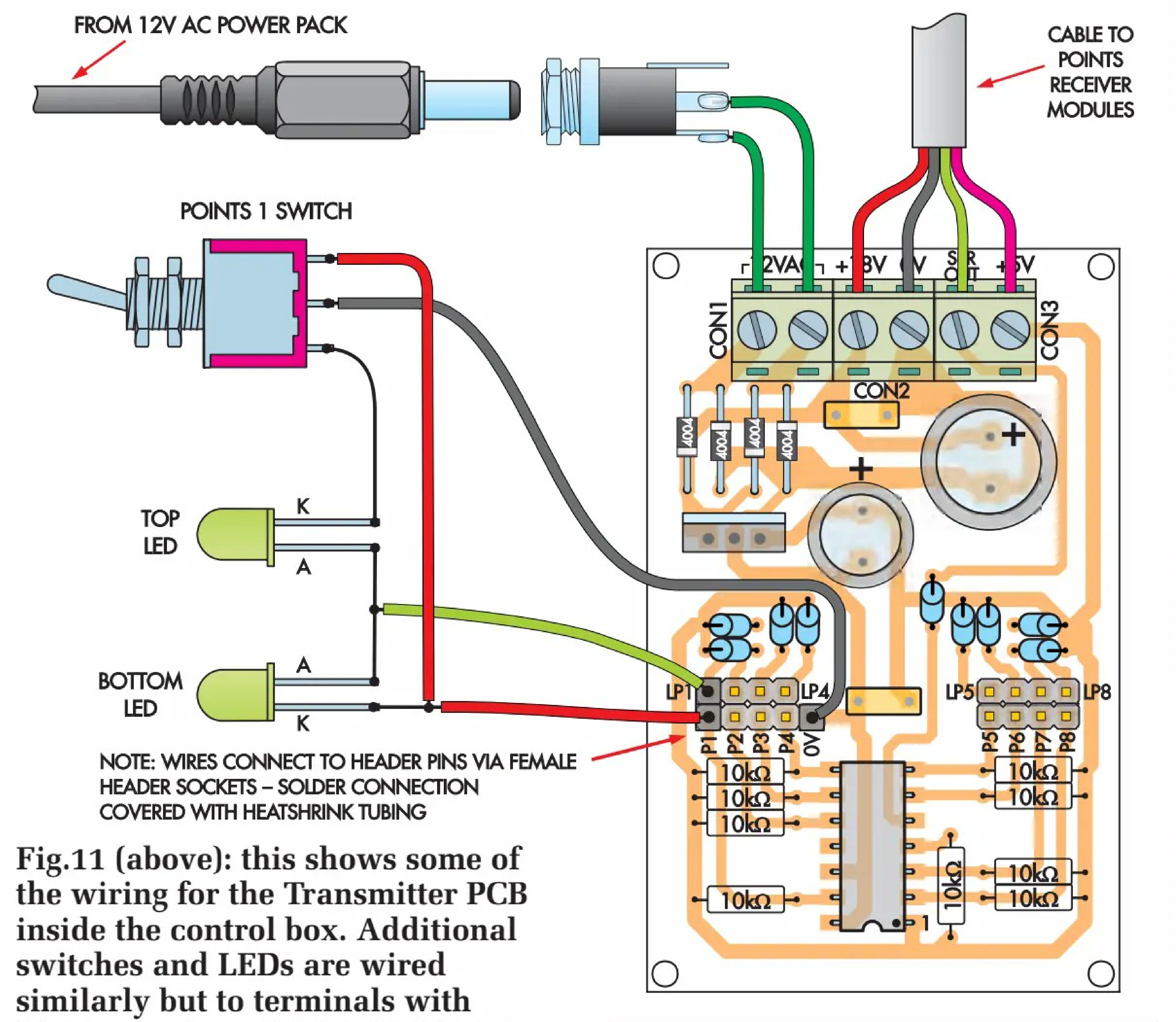
1 50mm length of $\frac{3}{32}$in (~2.38mm) square hollow brass tube
1 20mm length of 0.025in thick, 0.5in wide brass strip
1 20mm length of 20mm diameter solid aluminium rod
1 3mm green LED (LED17)
1 3mm red LED (LED18)

PoLabs
For more information or software download please visit
www.poscope.com/epe

PoKeys
Connect, Control
- USB
- Ethernet
- Web server
- Modbus
- CNC (Mach3/4)
- IO
- PWM
- Encoders
- LCD
- Analog inputs
- Compact PLC

Stepper motor drivers
Drive
- up to 256 microsteps
- 50 V / 6 A
- USB configuration
- Isolated
- up to 32 microsteps
- 30 V / 2.5 A

PoScope Mega1+
PoScope Mega50
Measure
- up to 50MS/s
- resolution up to 12bit
- Lowest power consumption
- Smallest and lightest
- 7 in 1: Oscilloscope, FFT, X/Y, Recorder, Logic Analyzer, Protocol decoder, Signal generator


FROM 12V AC POWER PACK
CABLE TO POINTS RECEIVER MODULES
POINTS 1 SWITCH
TOP LED
K
A
BOTTOM LED
A
K
12VAC
+13V
0V
SER OUT
+5V
CON1
CON2
CON3
4004
4004
4004
4004
LP1
LP4
LP5
LP8
P1
P2
P3
P4
0V
P5
P6
P7
P8
10kΩ
10kΩ
10kΩ
10kΩ
10kΩ
10kΩ
10kΩ
10kΩ
10kΩ
10kΩ
1

NOTE: WIRES CONNECT TO HEADER PINS VIA FEMALE HEADER SOCKETS – SOLDER CONNECTION COVERED WITH HEATSHRINK TUBING

Fig.11 (above): this shows some of the wiring for the Transmitter PCB inside the control box. Additional switches and LEDs are wired similarly but to terminals with higher numbers (P2/L2, P3/L3 etc).

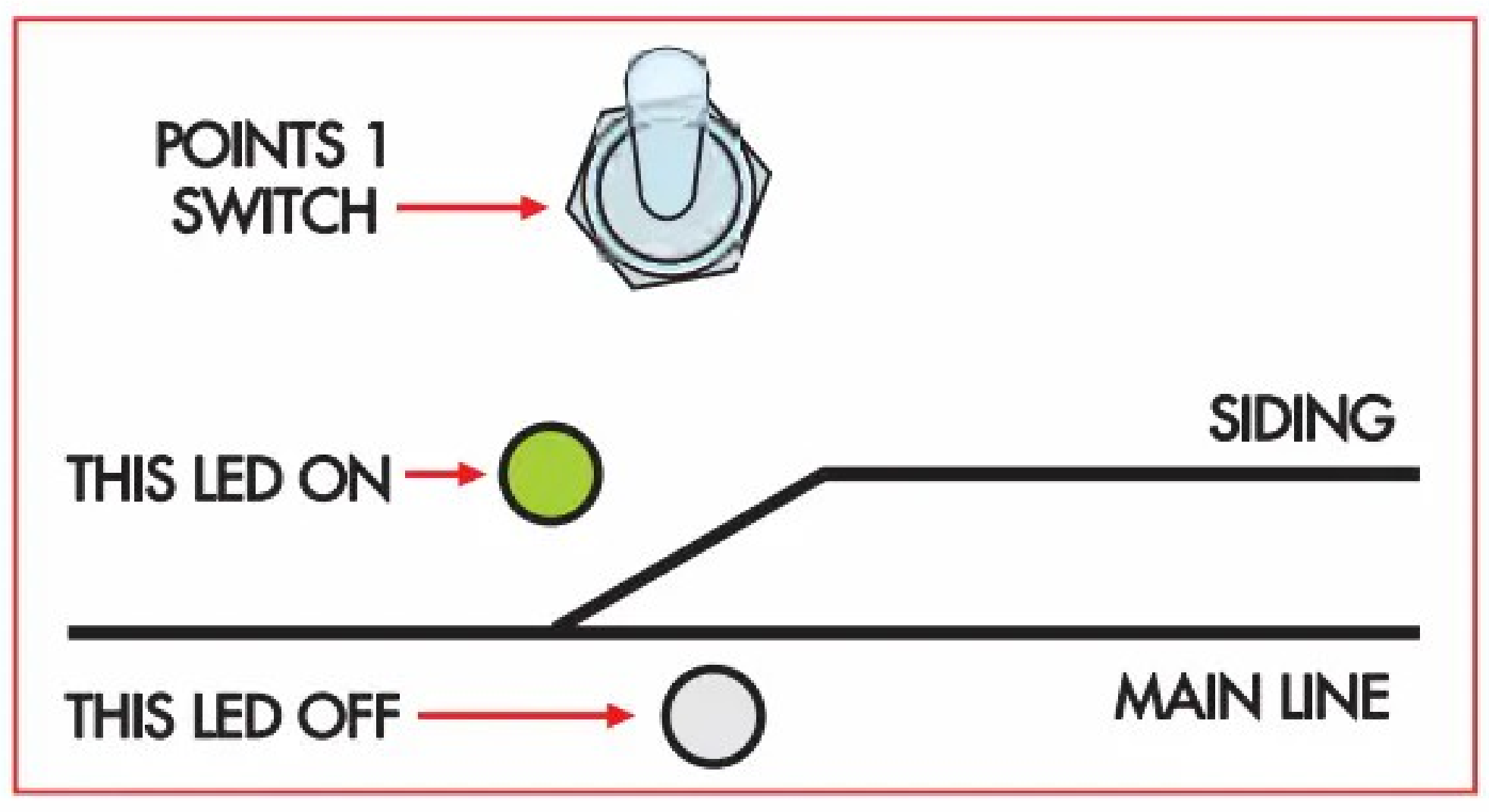

POINTS 1 SWITCH
THIS LED ON
THIS LED OFF
SIDING
MAIN LINE

Fig.12 (right): you will need to figure out where to position the switches and LEDs to suit your layout, but in general, this shows how they should operate. If yours does the opposite, reverse the switch or the wiring that is going to it.

length of heatshrink tubing and using a hot air gun to shrink it.

The 12V AC comes in via its attached plug and the socket that screws into the 8mm hole on the rear of the box. The connector must then be wired to the 12V AC screw terminals on the PCB.

Use four-way alarm cable or similar to make the connections between the Transmitter and the Receivers, as shown in Figs.3, 9 & 11. The cable exits the control box through the 6mm hole. The Receiver PCBs can be mounted underneath the layout.

Final testing

With all the points' switches in the up position, the green LEDs on the control box should indicate which way the points are switched, as shown diagramatically in Fig.12. Each signal should be green.

Changing a switch to the lower position should cause the associated set of points to change and the corresponding signal to go red. This should be reflected on the associated control box LED.

Due to the number of combinations of points types, motor positions and signals, you may find this isn't the case. If the problem is with the points, try swapping the points motor's red and black wires at the Receiver PCB.

If the problem is with the signal, that can be rectified by swapping the red and black wires from the signal where they connect to the associated Receiver PCB. **PE**

Table 1 – Receiver jumper settings

#	A	B	C
1	Jumper	Jumper	Jumper
2	Open	Jumper	Jumper
3	Jumper	Open	Jumper
4	Open	Open	Jumper
5	Jumper	Jumper	Open
6	Open	Jumper	Open
7	Jumper	Open	Open
8	Open	Open	Open

Subscribe to SILICON CHIP

SILICON CHIP
NOVEMBER 2024
heads or tails
Variable Speed Drive
for induction motors
Surf Sound Simulator

SILICON CHIP is one of the best DIY electronics magazines in the world. Each month is filled with a variety of projects that you can build yourself, along with features on a wide range of topics from in-depth electronics articles to general tech overviews.

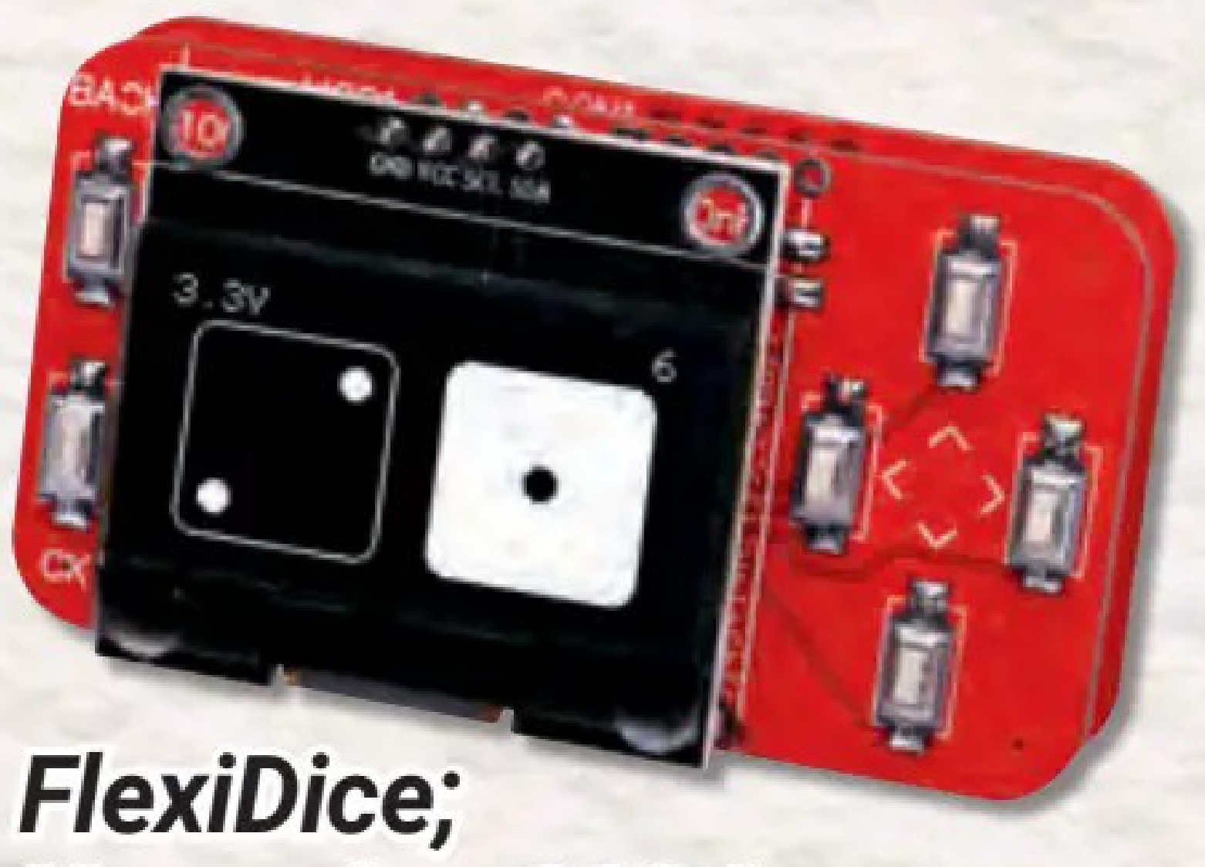
	Print	Combined	Online
6 months	\$100 ≈£52 ≈€62	\$110 ≈£58 ≈€68	\$50 ≈£26 ≈€31
1 year	\$195 ≈£102 ≈€120	\$215 ≈£112 ≈€132	\$95 ≈£50 ≈€58
2 years	\$380 ≈£200 ≈€235	\$415 ≈£217 ≈€255	\$185 ≈£97 ≈€115

- *Combined subscriptions include both the printed magazine and online access.*
- *Prices are in Australian dollars (AUD) unless otherwise specified.*
- *Prices listed are for everywhere in the world except Australia and New Zealand. View siliconchip.com.au/Shop/SubRates for a full list of current prices.*
- *Price estimates are just that and should only be used as a guide. We can only take payment in the form of Australian dollars.*

Try our Online Subscription – now with PDF downloads!

An online issue is perfect for those who don't want too much clutter around the house and is the same price worldwide. Issues can be viewed online, or downloaded as a PDF.

Published in SILICON CHIP



FlexiDice; November 2024

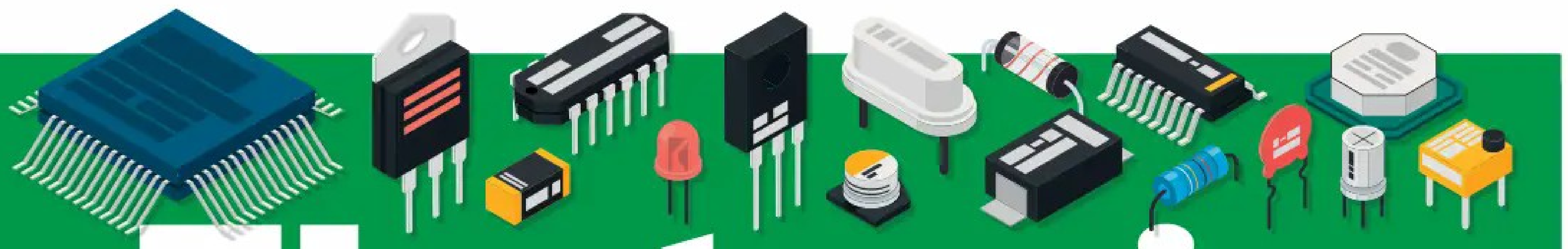
Surf Sound Simulator; November 2024

Micromite Explore-40; October 2024

DOWN UP OK MODE
SILICON CHIP
COMPACT CLOCK & TIMER

Compact OLED Clock; September 2024

To start your subscription go to siliconchip.com.au/Shop/Subscribe



Part 2: Op Amps

Precision Electronics

Last month, we examined broad concepts related to precision circuit design and built a simple circuit to measure current over a wide range. We'd like to improve its precision, and to do so, we need to learn a bit more about working with op amps – this month's topic.

By Andrew Levido

The simple circuit we devised last time to measure the current in a hypothetical power supply is shown in Fig.1. We used basic parts and achieved an average result. The error budget we calculated for this circuit is reproduced in Table 1.

The largest source of error was the op amp's input offset voltage, which contributed 7% out of the total 9% worst-case error. One way to improve this circuit would be to select a 'better' op amp. The trick, of course, is to decide what exactly we mean by better in this case. There are many hundreds of op amps described by their manufacturers as "precision op amps" – they can't all be just what we want!

The ideal op amp

At the macro level, it's handy to consider op amps as an ideal component. The ideal op amp has infinitely high input impedance, so no current flows into or out of the input pins. It has infinite differential-mode gain and zero common-mode gain or offset error. That means that the output is exactly zero when the input pins are at the same voltage, regardless of what voltage that is.

It also has zero output impedance, and the output voltage changes instantaneously when the differential input voltage changes, regardless of the output load impedance.

Considering op amps to be ideal is handy when analysing op amp circuits; all the classic op amp equations we use every day make this assumption. For example, we can calculate the gain of a non-inverting amplifier such as that in Fig.1 to be (1 + R1 ÷ R2) because we assume that the op amp is ideal.

Of course, real op amps are not ideal, although they come very close in many respects. We need to be aware of and understand the non-idealities when designing precision circuits.

Input bias and offset currents

Fig.2 shows the simplified circuits of two very common 'jellybean' low-cost op amps taken from their data sheets. Depending on where you get them, you can pay less than 10¢ per individual op amp for these useful devices, even in low quantities.

The LM324 (the quad version of the LM358), a bipolar transistor based op amp designed for single-supply operation, is shown at the top. Below it, is the TL074H JFET-based op amp (an improved release of the TL074 and the quad version of the TL071H/TL072H).

Both designs use a simple differential input transistor pair with current mirror loads, although the types of transistors used differ. Note that the LM324's input stage is inverted compared to that of the TL074H; we'll explain that shortly. Compound transistors (similar to Darlingtons) are used for the LM324 input pair for reasons that will also soon become apparent.

Inspecting the LM324 circuit, it should become obvious that some small current must flow out of the input terminals to bias the transistors on. This "input bias current" (I_B) can cause an unwanted voltage at the op amp's inputs by generating a voltage across the source impedance.

The effect of bias current naturally becomes more important when the source impedance is high.

For the LM324, I_B is specified to be less than -35nA at 25°C, up to -60nA over the operating temperature range (–40°C to +85°C). The usual convention is that positive currents flow into a pin, so these negative values imply that the bias current flows out of the pin.

The bias current is why you may see a resistor connected from the non-inverting input to ground in inverting amplifier circuits. The value is chosen to have the same resistance as the source network connected to

Table 1: error budget for the circuit in Fig.1 (repeated from last month)

		At Nominal 25°C		0-50°C (Nominal ±25°C)	
Error	**Nominal Value**	**Abs. Error**	**Rel. Error**	**Abs. Error**	**Rel. Error**
Shunt Resistor: Stackpole CSR1225 (1% 100ppm/°C)	100mΩ		1.00%		0.25%
Node A Voltage due to I × R shunt	**100mV**	**1mV**	**1.00%**	**0.25mV**	**0.25%**
Op Amp: LM7301 (V_{OS} ±6mV, 2μV/°C)	0mV	6mV		0.05mV	
Node A Voltage total (Line 2 + Line 3)	**100mV**	**7mV**	**7.00%**	**0.3mV**	**0.30%**
Op Amp Gain Resistor R1: Yageo RC0805 (1% 100ppm/°C)	1kΩ		1.00%		0.25%
Op Amp Gain Resistor R2: Yageo RC0805 (1% 100ppm/°C)	24kΩ		1.00%		0.25%
Op Amp Gain (R1 + R2) ÷ R1	**25**	**0.5**	**2.00%**	**0.125**	**0.50%**
V_{OUT} (Line 4 × Line 7)	**2.5V**	**0.225V**	**9.00%**	**0.02V**	**0.80%**

the inverting input so that any voltage due to the bias current is equal on both inputs and therefore cancels out.

Without that, a differential temperature drift can occur, making trimming the op amp almost impossible!

However, the bias currents at each input will never be precisely equal due to manufacturing tolerances. I_B is actually defined as being the average of the two bias currents. The difference between them is the "input offset current" (I_{OS}). For the LM324, this is specified to be no more than ±5nA over the full temperature range.

You may have now figured out one of the main reasons for the LM324's use of compound transistors – they have a much lower base current for the same collector current, so using compound transistors here helps to minimise that pesky input bias current.

Even so, the input bias current of the FET op amp is much lower than that of a bipolar op amp due to the diodes at JFET gates being reverse-biased during normal operation. For the TL074H, the maximum bias current is ±120pA at 25°C and ±5nA (±5000pA) over the full temperature range.

Notice that while the input bias current for the FET op amp is lower at room temperature, it is much more sensitive to temperature. The input offset current is also proportionally higher as it's harder to match JFETs than it is to match BJTs.

CMOS op amps are available that use Mosfets for the inputs, which have an even higher gate impedance, and thus lower bias currents (in the femtoamps!), like the LMC6482.

Input common-mode range

The other thing that should be apparent is that the range of input voltages over which the differential pair can operate is limited. Looking at the LM324, the input transistors' base-emitter junctions will be forward-biased with the inputs at the negative rail (the ESD protection diodes will prevent them from going much lower).

However, there must be some voltage drop across the V_{BE} junctions of the input transistors and the 6μA current source, so there will be an upper limit on the input voltage somewhat lower than the positive supply. Above this limit, the transistors will be biased off.

This active input voltage range is known as the common-mode voltage range (V_{CM}) and is specified for the LM324 to be [V–, V+ – 2.0V] (over its operating temperature range). That means the input range extends from zero (V–) to 2V less than the positive supply voltage.

Op amps designed for single-supply operation often have this 'inverted' PNP or P-channel input stage with V_{CM} extending to 0V. The TL074H input stage also has a V_{CM} limitation, but because it uses N-channel JFETs in a conventional differential pair, the limitation is on the negative rail side. The V_{CM} of the TL074H is [V– + 1.5V, V+].

Exceeding the common mode range can cause very odd behaviour in some devices, so you generally must ensure your input signals stay within the op amp's rated V_{CM} range.

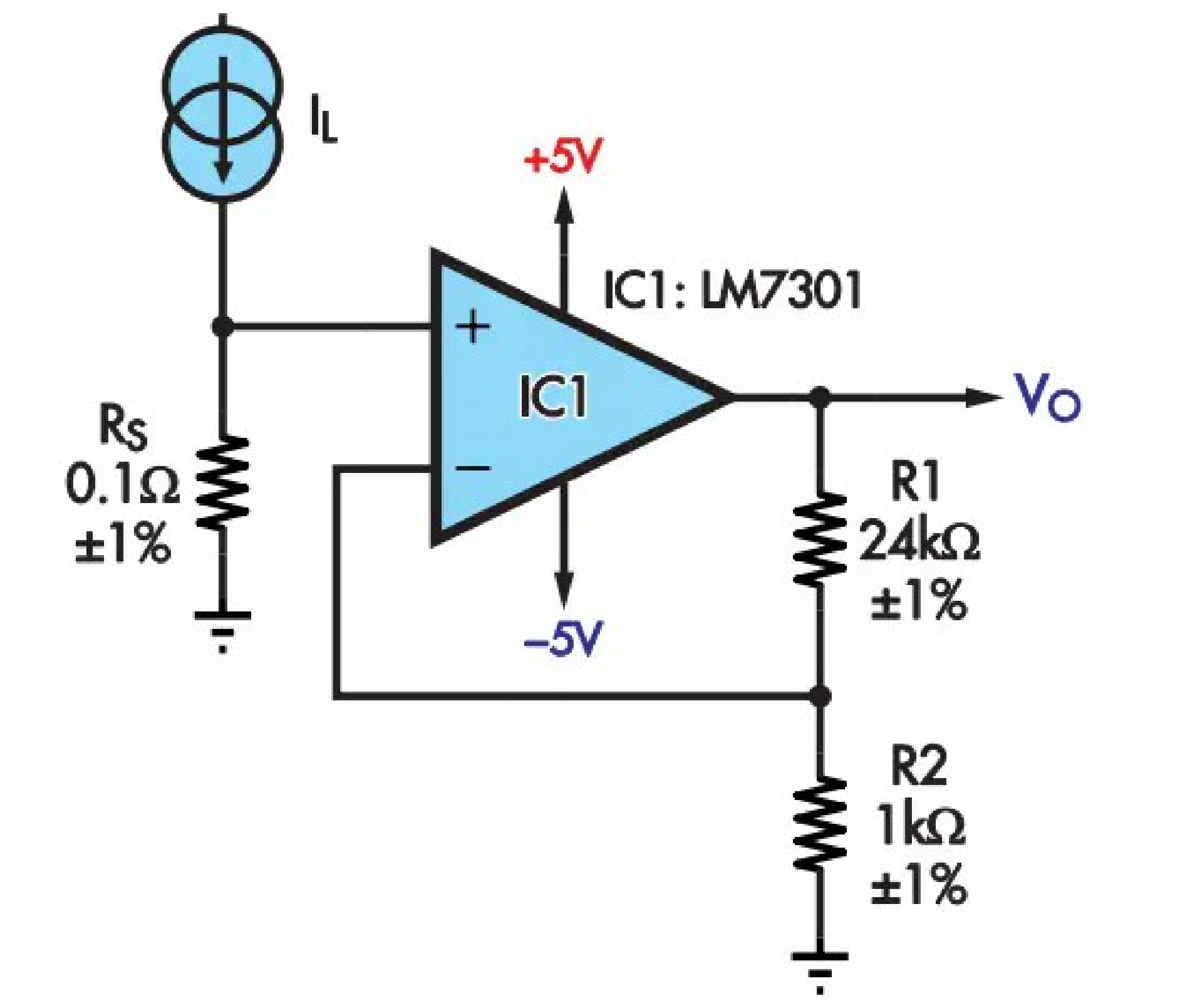


Fig.1: our first attempt at sensing current from the last article. This circuit used simple parts and achieved very average results with untrimmed errors in the order of 2% at 25°C. We can do much better by selecting better parts.

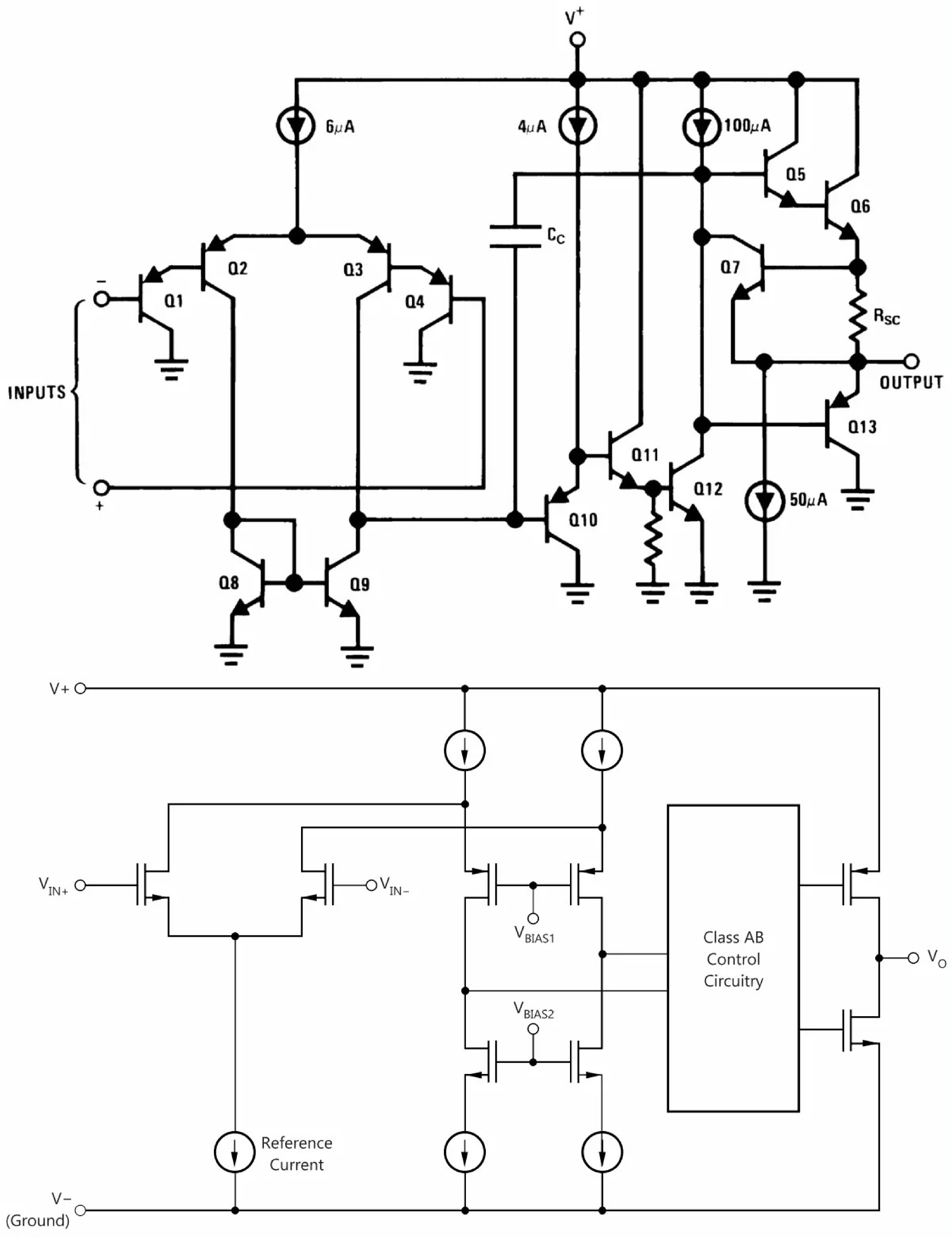


Fig.2: these simplified internal circuits of the LM324 (top) and TL074 (bottom) op amps show the input differential pairs and push-pull output stages. The LM324's input stage is inverted compared to the conventional differential pair of the TL074 because the LM324 is designed for single-supply operation.

Precision Electronics, part two

This can become a problem when operating from low-voltage supplies, which are common these days. For example, the LM324 will work with a supply as low as 3V, but in this case, the V_{CM} range will be just [0V, 1V]. You should also be careful if you intend to use an op amp designed for dual-supply operation in a single-supply circuit, as the V_{CM} may not extend to either voltage rail.

Rail-to-rail input op amps

Plenty of op amps claim to have 'rail-to-rail' inputs, such as the LM7301 we used in the first instalment of this series. These op amps usually have two differential pairs at the input – both NPN and PNP in the case of bipolar op amps, or an N-channel FET and a P-channel FET in the case of FET-input op amps.

These work well in many applications, and their V_{CM} range includes both supply rails, but they have a few peculiarities you should be aware of.

Because they effectively switch between two input stages, their input bias current and input offset voltage can show unusual behaviour. Fig.3 shows that, for the LM7301, the input bias current reverses polarity a volt or so below the positive supply rail. The graph also shows that the input offset voltage kicks up at the same point as the op amp switches from one input circuit to another.

We saw in the last article that one of the keys to precision circuit design is to trim out constant errors (usually in software). The type of non-linearities that rail-to-rail input op amps can introduce can make this trimming very difficult. By all means, use them when needed, but exercise caution.

Input offset voltage (V_{OS})

This brings us to input offset voltage, which is causing most of the problems with our test circuit. Identical input transistors with identical collector or drain currents at the same temperature should have identical base-emitter or gate-source characteristics.

Unfortunately, manufacturing variances mean neither the transistors nor the mirrored currents will be perfectly identical, so there will be a difference in V_{BE} or $V_{GS(TH)}$ between the two input transistors.

The impact of these differences means that even with the input pins connected together, the output of an op amp will saturate at one supply rail or the other (and you can't predict which). If the loop is closed, the output voltage will be the difference in V_{BE} or $V_{GS(TH)}$ multiplied by the closed-loop gain.

This difference can be modelled as a small voltage source in series with one of the inputs of otherwise perfectly matched input transistors. This is the definition of input offset voltage (V_{OS}).

In the case of the LM324, V_{OS} is specified to be ±2mV (worst case) with ±7μV/°C of temperature drift, whereas for the TL074H, it is ±4mV (worst case) with ±2μV/°C drift. JFET op amps usually have a higher V_{OS} since a JFET's (or Mosfet's) $V_{GS(TH)}$ parameter is less tightly controlled than the bipolar transistor's V_{BE}.

Reducing input offset voltage

Op amp offset voltage is caused by unavoidable manufacturing variation between the input transistors, so you might think we are stuck with it. However, op amp designers are a pretty creative group, and they have come up with some very clever circuits to minimise voltage offset and, more importantly, minimise offset voltage drift with temperature.

The first technique is laser trimming, where the offset voltage of an op amp is measured after manufacturing and then a laser is used to adjust the value(s) of onboard resistor(s) to compensate for it – a little like having a tiny trimpot onboard the IC that's set before it's packaged.

Doing this costs money, so high-precision op amps tend to cost more but can have very low offset voltages (and low drift), down to the sub-microvolt level in some cases. However, as it's a static adjustment, it does nothing to improve temperature drift. An example of a laser-trimmed op amp is the OPA277PU, with a maximum V_{OS} of ±20μV and a maximum V_{OS} drift of ±0.15μV/°C.

The second technique is auto-zeroing or auto-nulling, as shown in Fig.4. Along with the main op amp, OAa, the package includes nulling op amp OAb. During one phase of the clock (phase A), the inputs of OAb are connected together, so its output is its offset voltage, which is stored in capacitor C1.

During the other phase (phase B), OAb measures OAa's offset and stores it on capacitor C2. The voltage on capacitors C1 and C2 are used to null out the V_{OS} of the nulling and the main amplifiers, respectively.

The nice thing about this approach is that the primary signal through the main op amp, OAa, is never switched. OAb alternately nulls itself and OAa, more or less eliminating the offset regardless of how it changes over time.

Another technique is the chopper approach, shown in Fig.5. Again, the amplifier is broken into sections OAa and OAb. On clock phase A, the two stages are connected such that neither stage inverts the input signal, while on phase B, they are connected such that both stages invert the signal.

The result is that the output signal always has the right sense, but the offset voltage across the capacitor alternates in polarity and thus averages to zero.

These circuits (and their variations)

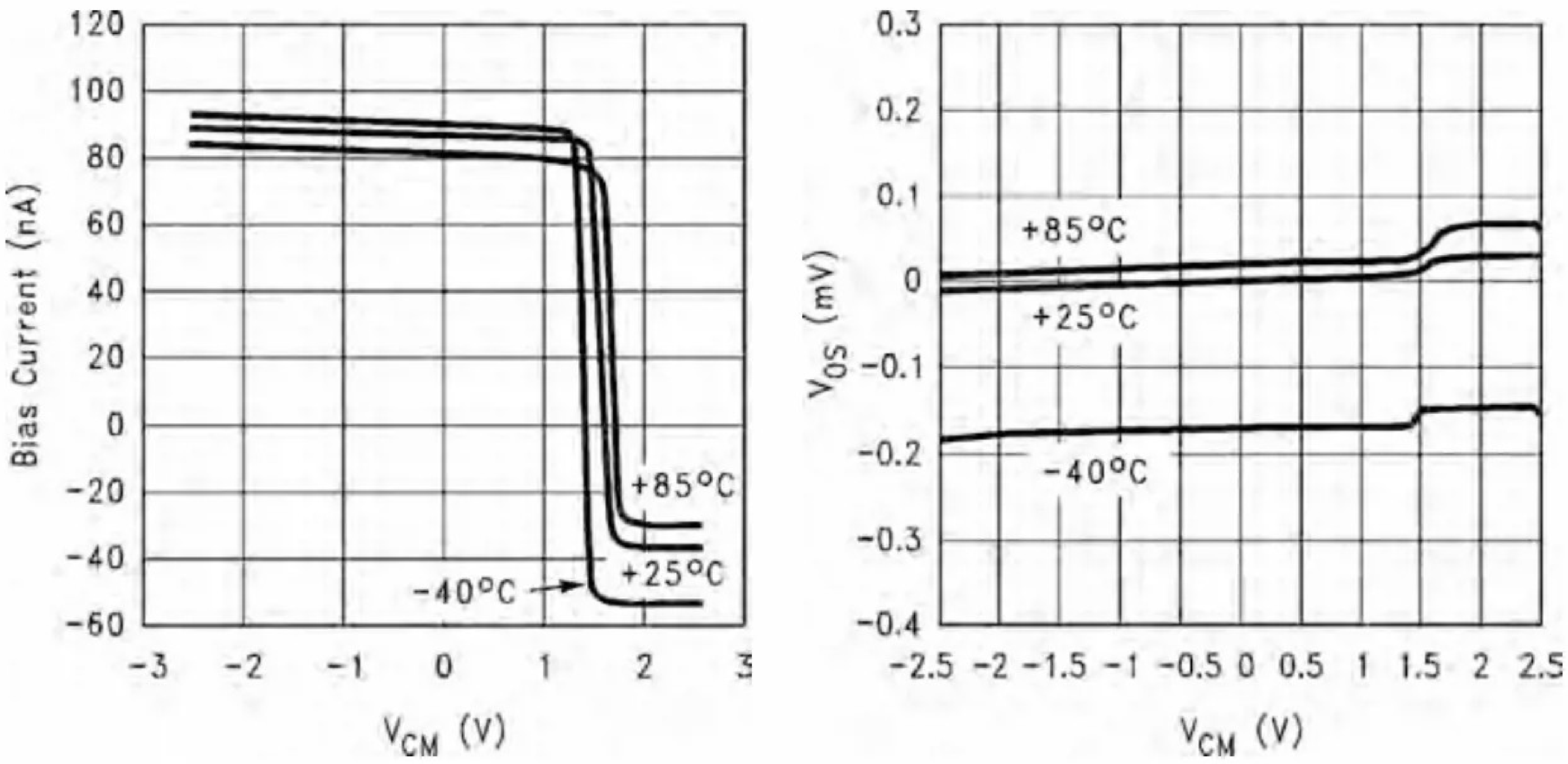


Fig.3: this extract from the LM7301 data sheet shows how the input bias current abruptly switches polarity, and the input offset voltage kicks up when the input common-mode voltage gets to within a volt or so of the positive rail. This results from the rail-to-rail input stage switching between the normal and inverted differential pairs. Both plots are for ±2.5V supply rails.

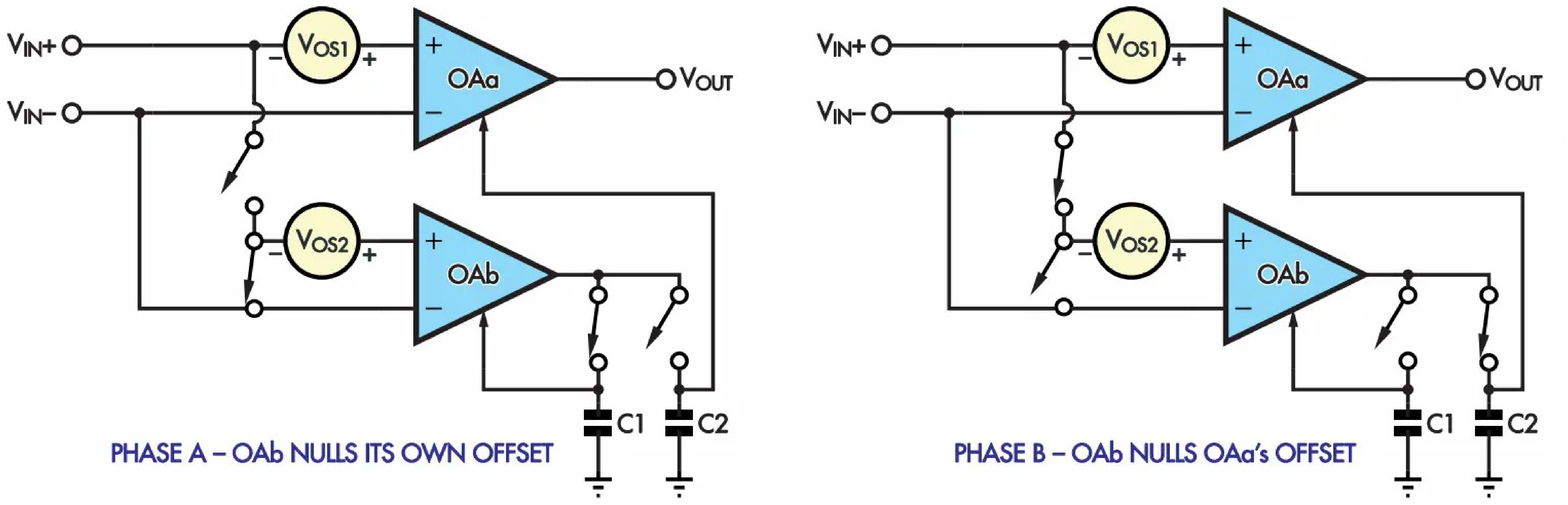

VIN+
VIN−
VOS1
VOS2
OAa
OAb
VOUT
C1
C2
PHASE A – OAb NULLS ITS OWN OFFSET
PHASE B – OAb NULLS OAa's OFFSET

Fig.4: auto-zero op amps have a second nulling amplifier that alternatively nulls its own V_{OS} and that of the main amplifier. The result is extremely low V_{OS} and, more importantly, very low V_{OS} drift with temperature.

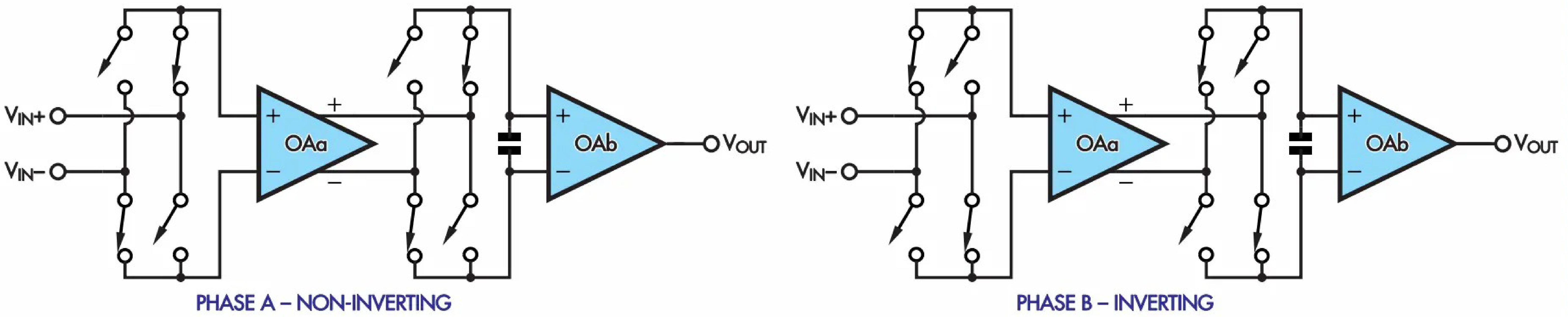


Fig.5: a chopper op amp reduces the overall V_{OS} by alternating the polarity of the signal through two stages. The output always has the same sense, but the offset voltage at the capacitor alternates in polarity and averages to zero.

can achieve remarkable results in terms of low offset. The AD8551, for example, uses a nulling approach and has a maximum V_{OS} of ±5μV with a ±40nV/°C tempco. The LTC2057 uses a chopper configuration and achieves even better results, with a maximum V_{OS} of ±4μV with ±15nV/°C tempco. These figures are around 1000 times better than the jellybean op amps.

The downside is that some switching artefacts will appear in the output, so they don't have the best noise performance. They also tend to be limited in bandwidth and require a higher supply current, either of which could be a concern if you are building a high-bandwidth or an ultra-low power design.

They are also more expensive, at around £2.50 for the LTC2057 and £3.25 for the AD8551.

Input impedance

We also need to consider the input impedance. Input impedance is the small-signal open loop impedance seen at the input. It is specified as a common-mode impedance (inputs tied together to ground) and a differential-mode impedance (between inputs). The common-mode impedance is usually the higher of the two.

Differential mode impedance is not usually a concern at low frequencies, as negative feedback forces the voltage between the inputs to zero, effectively bootstrapping the differential impedance to a very high value.

Imperfect output stages

You can see from Fig.2 that the output voltage of our op amps will not be able to swing all the way to either power rail due to the finite saturation voltage of the output transistors and the drop across the output current limiting circuits. In the case of the LM324, you can also see that the output swing may not be symmetrical.

The output swing is generally described in terms of the voltage 'headroom' or how close the output voltage can approach the supply rails with some given load.

With a 10kΩ load, the LM324 can reach within 0.15V of the negative rail but can only get to within 1.5V of the positive rail. On the other hand, the TL074H can get to within 0.25V of either rail with the same load.

Some op amps offer output swings much closer to the rails than these basic parts, typically to within 50mV of the rails into 10kΩ. Still, no op amp will swing completely to the rail – a fact that caught us out in the first iteration of our test circuit in the previous article in this series (sometimes you can help them get closer with a resistor tied to one rail or the other, but it only works for one rail!).

Op amp data sheets may show a figure for open-loop output impedance (125Ω in the case of the TL074H), but you can't use this directly to determine the maximum output current or swing in closed-loop applications. That is because the effective output impedance is reduced by the loop gain.

What may be important in your application is the maximum current that the op amp can source or sink, usually specified as a short-circuit current. This is typically in the ~20mA range (it's ±26mA for the TL074H and ±40mA for the LM324). There are high-current op amps, some sourcing and sinking several amps, but they are rare and can be pricey.

Gain, bandwidth & slew rate

An op amp's open loop voltage gain is not infinite, but it is pretty high, typically in the order of 100dB to 120dB at DC but dropping linearly to unity at a frequency f_T, sometimes called the gain-bandwidth product (GBW).

For stability, most op amps have internal dominant pole frequency compensation that reduces the op amp gain to 0dB at a frequency where the phase shift is well below 180°.

Fig.6 shows a curve for a typical op amp. The open loop gain at DC is a little over 110dB, dropping from about 2Hz more-or-less linearly to f_T, which is a little over 1MHz. In this

Table 2: error budget for the improved circuit in Fig.7		At Nominal 25°C		0-50°C (Nominal ±25°C)	
Error	**Nominal Value**	**Abs. Error**	**Rel. Error**	**Abs. Error**	**Rel. Error**
Shunt Resistor: RESI PCSR2512DR100M6 (0.5% 15ppm/°C)	100mΩ		0.50%		0.038%
Node A Voltage due to I × R shunt	**100mV**	**0.5mV**	**0.50%**	**0.0375mV**	**0.038%**
Op Amp: LTC2057 (V_{OS} ±4μV, 15nV/°C)	0μV	4μV		0.375μV	
Node A Voltage total (Line 2 + Line 3)	**100mV**	**0.504mV**	**0.50%**	**0.0379mV**	**0.038%**
Op Amp Gain Resistor R1/R2: Vishay ACASA 1000S1002P1AT (0.1%, 0.05% matched, 15ppm/°C)	26Ω		0.05%		0.038%
Op Amp Gain (R1 + R2) ÷ R1	**26**	**0.013**	**0.05%**	**0.0098**	**0.038%**
V_{OUT} (Line 4 × Line 6)	**2.6V**	**0.0144V**	**0.55%**	**0.002V**	**0.075%**

case, the phase shift at f_T is -85°. The op amp would oscillate if the phase shift reached -180° and the gain was still greater than unity.

The difference between the phase shift at f_T and -180° is known as the phase margin; it is 95° in this case. This is the maximum phase shift your feedback circuit can safely introduce if you want the op amp to remain stable.

It's important to remember that the blue curve is the open loop gain. The orange line illustrates a typical closed-loop gain, in this case, a gain of 10 (or 20dB). The closed loop gain is flat to about 100kHz, which is what you would expect with a gain-bandwidth product of 1MHz.

One side effect of this dominant pole compensation is that it limits how quickly the op amp output can change in response to a change in the differential input voltage. This is known as the slew rate and it is typically measured in volts per microsecond (V/μs). The LM324 has a GBW of 1.2MHz and a slew rate of 0.5μV/s, while the TL074H has a GBW of 5.25MHz and a slew rate of 20V/μs.

Op amps with a higher GBW usually (but not always) draw more supply current, and conversely, low-power op amps have a lower GBW. If you want an op amp with a low power draw and a high GBW, be prepared to pay extra.

Choosing an op amp

There is a lot to consider when choosing an op amp, and there are a vast number of options, so where do we start? I suggest you begin by narrowing down the parameters you really care about. Taking our current-measuring circuit as an example, we don't care too much about the AC parameters, such as bandwidth and slew rate, since we are interested in DC measurements.

With ±5V supplies and a signal ranging from 0V to around 2.5V, we also don't have any stringent V_{CM} or output swing requirements, so we can set them aside. As long as the input and output voltages are within a couple of volts of the rails, we will be OK.

Since our source impedance is very low due to the low-resistance current shunt, the contribution to error from input bias and offset currents will be negligible. So, our primary focus should be on V_{OS} and, more importantly, its drift with temperature.

Cost and availability are also factors that should not be ignored. It so happens that I had a few LTC2057s on hand, and we have already seen their V_{OS} figures are impressive, a maximum of ±4μV with ±15nV/°C tempco.

Other improvements

While we are at it, we should look also at the rest of the components. The shunt resistor has a tolerance of ±1% and a tempco of 100ppm/°C. Low-value resistors with very tight tolerances (say in the 0.1% range or better) are extremely expensive, so they are not worthwhile since this kind of error

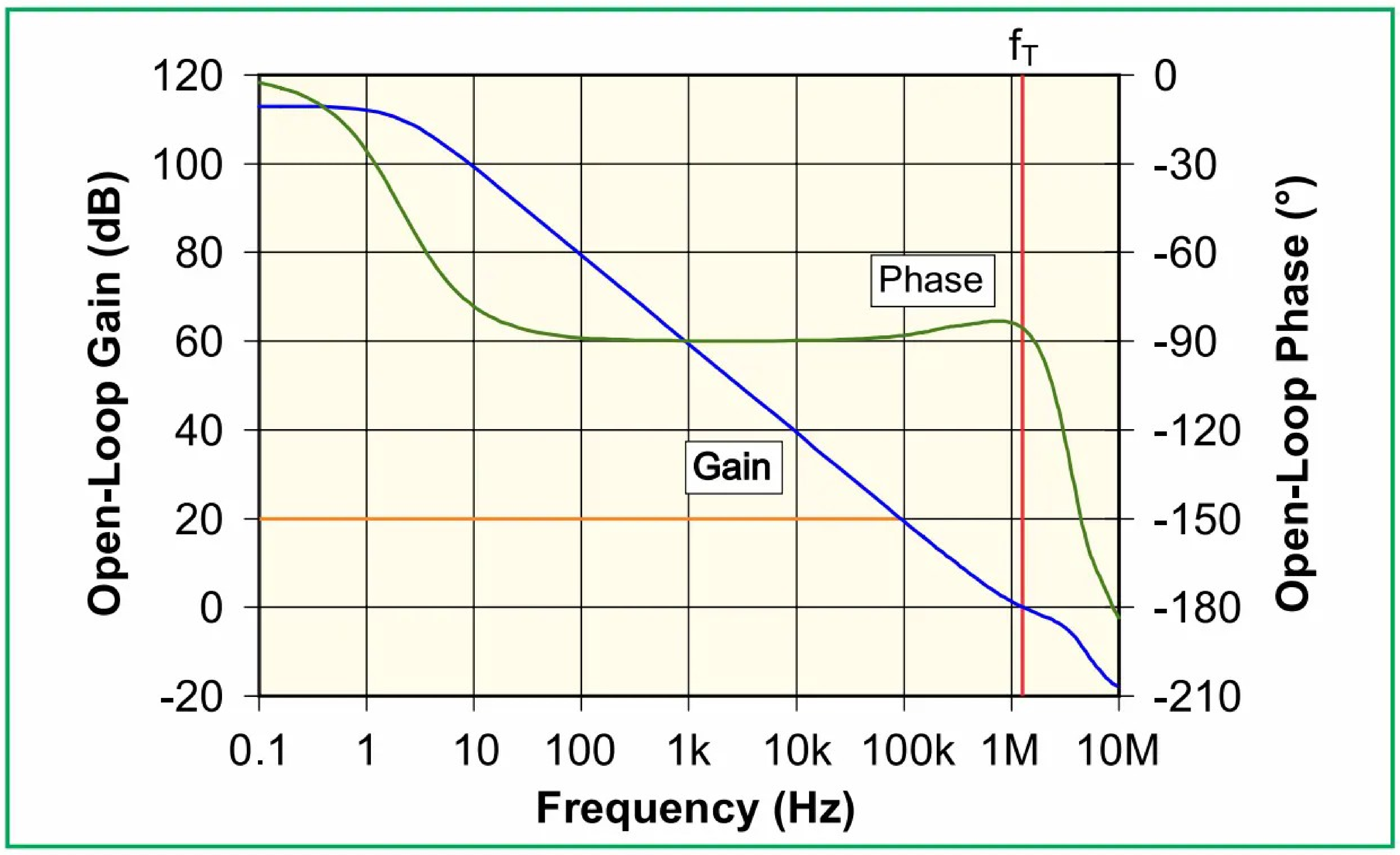


Fig.6: most op amps have an open-loop gain dominated by a low-frequency pole that ensures the gain (blue curve) falls to 0dB well before the phase shift reaches -180°. This ensures the op amp remains stable at any closed-loop gain. The frequency at which this occurs is known as the f_T (the transition frequency) or gain bandwidth product (GBW).

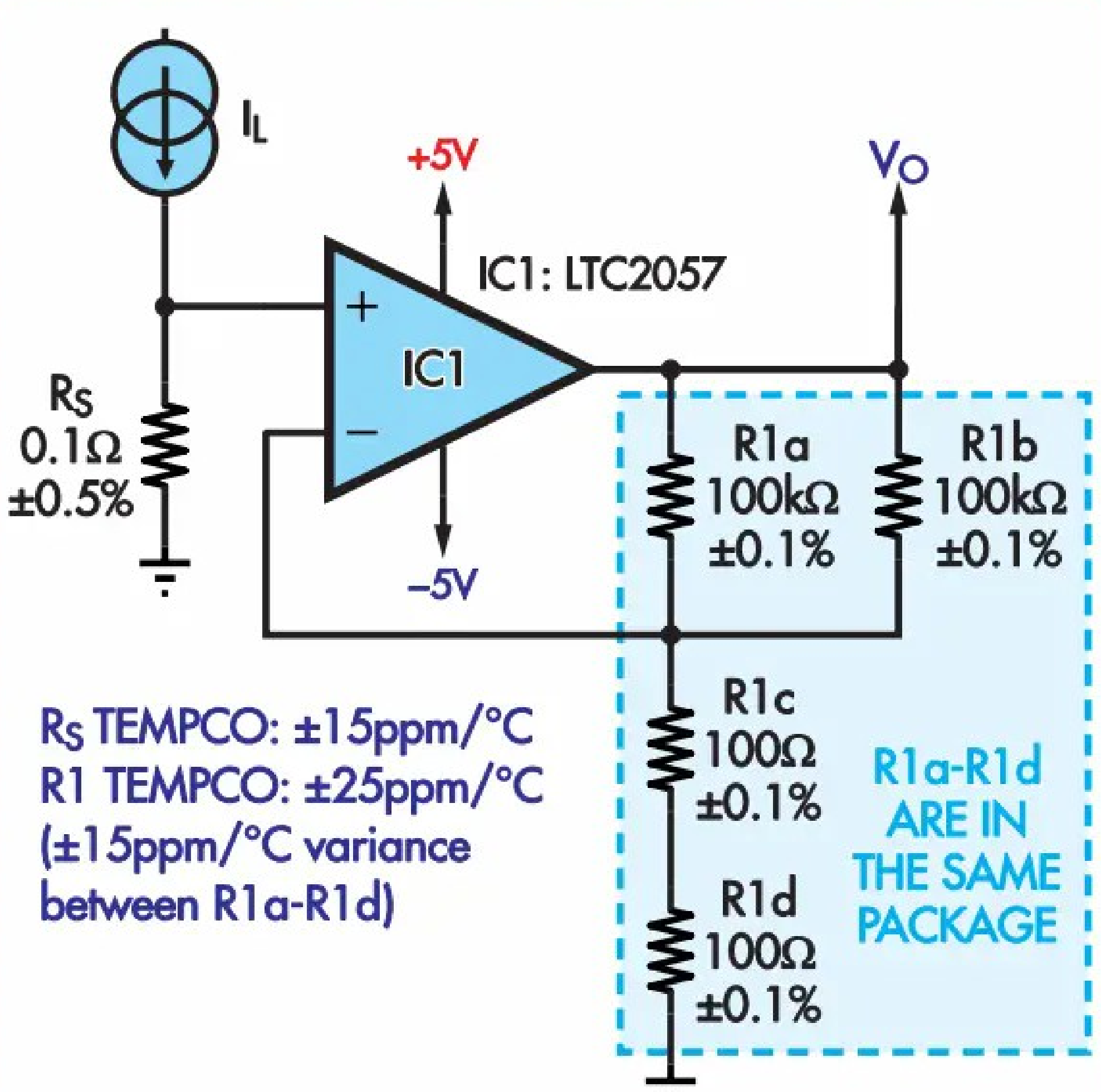


Fig.7: the improved version of the circuit from Fig.1. The LTC2057 has much better offset performance and the gain resistor ratios have much better temperature tracking. The resulting circuit will have better untrimmed accuracy but, more critically, less drift with temperature.

can be trimmed out. However, it is possible to get a resistor with a much lower temperature coefficient at little extra cost.

For example, the 100mΩ resistor in Table 2 has a tempco of ±15ppm (and a slightly better tolerance of 0.5%) for about £1.65 each in quantities of 10.

We can also do better with the tempco of the gain-setting resistors. Again, we could splash out on expensive 0.01% resistors, but that would be wasting money. What matters most to us is the temperature coefficient. Further, what we really care about is the tempco of the ratio of the gain setting resistors, since if they drifted high or low together at precisely the same rate, the gain would not change.

I like to use low-cost matched resistor arrays for this type of application. These have a small number of laser-trimmed resistors on a common substrate. They are well-matched in value and likely to be at the same temperature, thus tracking each other well.

The Vishay ACASA range of resistors fits the bill perfectly. They are low in cost, have a 0.1% overall tolerance, and are matched to within 0.05%. The most readily available subset has an absolute temperature coefficient of ±25ppm and a relative temperature coefficient of ±15ppm. An array of four such resistors costs around 50p each in lots of 10.

We can't quite get the 24:1 ratio of R1:R2 in the original circuit since the ACASA range comes in only a few values, but I can get an array consisting of two 100Ω and two 10kΩ resistors that can be arranged to create a 25:1 ratio. The result is a gain of 26 instead of 25, but that should not be a problem since we can scale and offset our readings in software. Fig.7 shows the revised circuit diagram.

I have put these components into the error budget table (Table 2), which shows we can expect an untrimmed precision of ±0.55% at 25°C with a further 0.075% drift over the 0°C to 50°C temperature range. The overall untrimmed precision is about 20 times better than before, and the temperature performance is about 10 times better than the previous design.

The error is dominated by the initial shunt tolerance, which will have to be trimmed out.

Experimental results

The test results are shown in Table 3. To measure circuits of this precision, you need good instruments and a carefully designed measurement setup. The worst-case error is just under 0.2% at full scale, and it increases steadily, suggesting a gain error of some kind. These values are plotted in Fig.8, along with a line of best fit.

This suggests we have an offset error of about -1.3mV (about 50µV on the input side of the op amp) and a gain error of about 0.2%, most likely due to the shunt resistor tolerance.

Table 4 shows the results if we apply a fixed offset and gain correction to the measured values. That gives a trimmed precision better than ±0.04%. From the error budget, you will see that the tempco is of the same order (±0.075%), so we can achieve an overall precision of a little over 0.1%. That is a tenfold improvement over our initial circuit.

Measured Data		Error	
Current	**V_{OUT}**	**Abs.**	**Rel.**
0.076	-1.100	-1.3	-0.05%
99.810	258.380	-1.1	-0.05%
199.795	519.380	-0.1	0.00%
299.311	779.470	1.3	0.05%
400.073	1040.64	0.5	0.02%
500.314	1302.00	1.2	0.05%
600.575	1563.33	1.8	0.07%
700.995	1825.17	2.6	0.10%
801.785	2087.33	2.7	0.11%
902.612	2350.11	3.3	0.13%
1003.431	2613.58	4.7	0.19%

Table 3 – measurements from the Fig.7 prototype. ***Units: Current (mA), V_{OUT} (mV), Absolute (mV), Relative (%).***

Measured Data		Error	
Current	**V_{OUT}**	**Abs.**	**Rel.**
0.0	0.2	0.0	0.00%
97.9	259.2	-0.4	-0.01%
198.2	519.6	0.1	0.01%
298.3	779.2	1.0	0.04%
398.3	1039.8	-0.4	-0.02%
498.3	1300.6	-0.2	-0.01%
598.3	1561.4	-0.1	0.00%
698.0	1822.7	0.1	0.00%
798.0	2084.3	-0.3	-0.01%
898.0	2346.5	-0.2	-0.01%
998.0	2609.5	0.6	0.02%

Table 4 – readings after applying fixed offset and gain corrections.

Next time, we will look at how we could measure this current if the shunt were in the positive supply instead of being ground-referenced. That is often desirable so the load can share a common ground with the supply (which would be necessary if both were Earthed).

References

- AD8551 data sheet: https://pemag.au/link/ac01
- "Demystifying Auto-Zero Amplifiers Part 1": https://pemag.au/link/ac02
- LM324B data sheet: https://pemag.au/link/ac03
- LM7301 data sheet: https://pemag.au/link/ac04
- LTC2057 data sheet: https://pemag.au/link/ac05
- TL074H data sheet: https://pemag.au/link/ac06

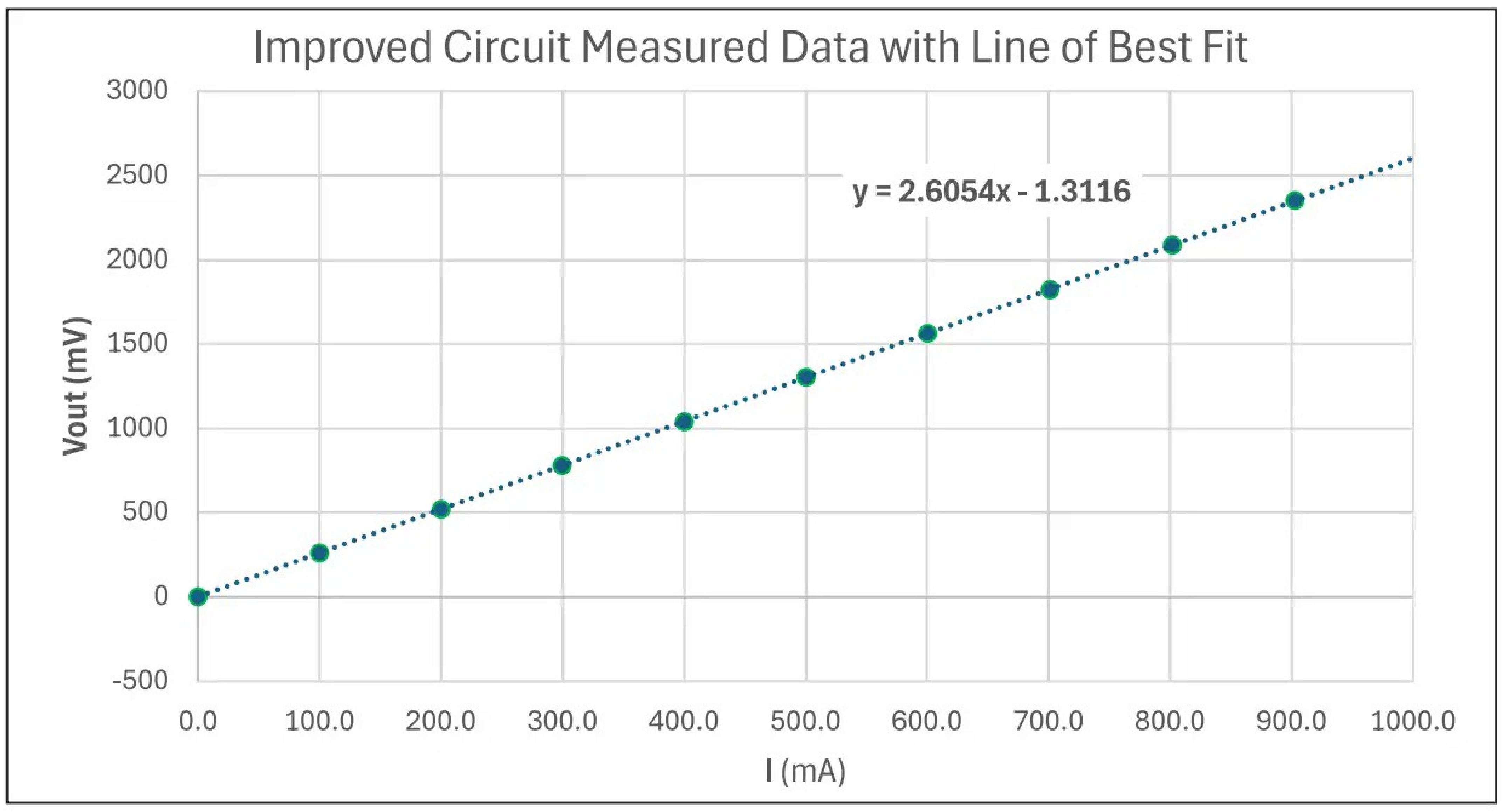
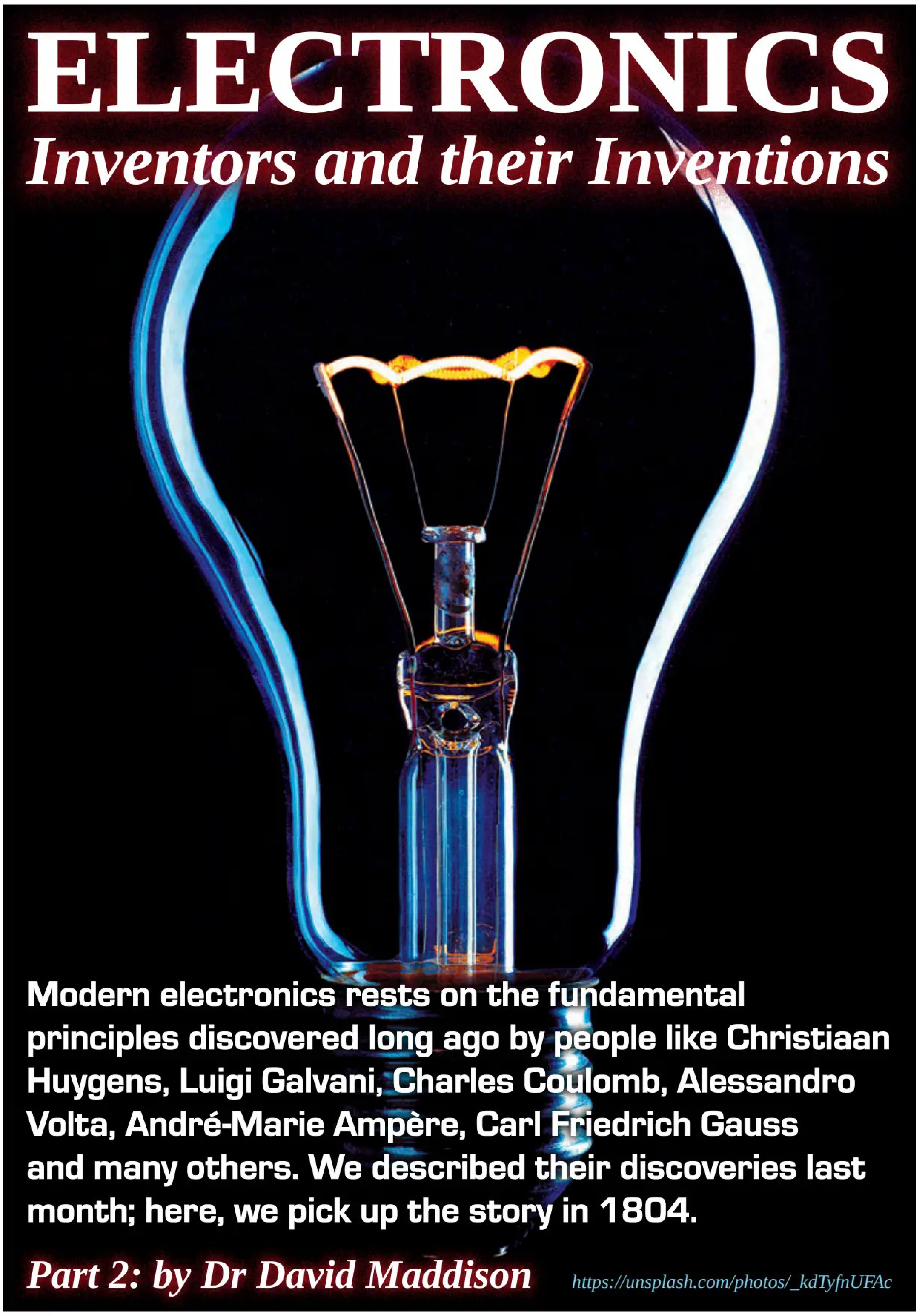


Fig.8: a plot of the data points from Table 3 with a line of best fit. This suggests an offset of -1.3mV and a gain error of about 0.2%. We can use these figures to trim the measured values and eliminate fixed errors.



ELECTRONICS

Inventors and their Inventions

Modern electronics rests on the fundamental principles discovered long ago by people like Christiaan Huygens, Luigi Galvani, Charles Coulomb, Alessandro Volta, André-Marie Ampère, Carl Friedrich Gauss and many others. We described their discoveries last month; here, we pick up the story in 1804.

Part 2: by Dr David Maddison

https://unsplash.com/photos/_kdTyfnUFAc

This series of articles started last month and will likely run to around six parts. That's because there are so many people who contributed to our understanding of electricity and electronics over the last few hundred years.

The first part last month started in 624BCE, although there were only two entries before 1544, the birth year of William Gilbert. Gilbert essentially coined the term "electricity".

Other important people in the field of electricity mentioned include Benjamin Franklin, Luigi Galvani, Charles Coulomb, Alessandro Volta, John Dalton, Thomas Johann Seebeck, André-Marie Ampère, Carl Friedrich Gauss, Hans Christian Ørsted, Georg Simon Ohm, Michael Faraday, Samuel Morse, Joseph Henry, Charles Wheatstone and Wilhelm Eduard Weber.

As with the last article, the people will be presented in order of their year of birth, although that means that their discoveries won't necessarily be listed in chronological order.

The discoveries and inventions in this article date from the 1830s, a point at which electricity and magnetism were already fairly well understood, but what we would call electronics today was still a field in its infancy.

Robert Davidson *1804-1894*
electric train

Built the first electric locomotive in 1837, which was powered by galvanic cells. He then built a full-sized train in 1842 called "Galvani"; it was around 5m long.

Edward Davy *1806-1885*
electric relay

He worked on the electric telegraph during 1835-1838 and was considered a contributor equal to Cooke and Wheatstone by J.J. Fahie. In 1837, he invented the electric relay, or "electric renewer" as he called it, as part of his telegraph system. In 1838, he migrated to Australia.

Duchenne de Boulogne *1806-1875*
electrophysiology

Experimented with electrical stimulation on parts of the human body and is considered a pioneer in electrophysiology. He first published his work, "*De l'electrisation localisée...*" in 1855.

You can read that book in the original French at **pemag.au/link/abn8**

Alfred Lewis Vail *1807-1859*
improved on Morse Code

Was involved with Samuel Morse in commercialising telegraphy 1837-1844. He enhanced Morse Code by simplifying the alphabetic system, making it easier to decode, along with other physical improvements.

Antonio Meucci *1808-1889*
telephony and dynamic microphone

According to some, he was the

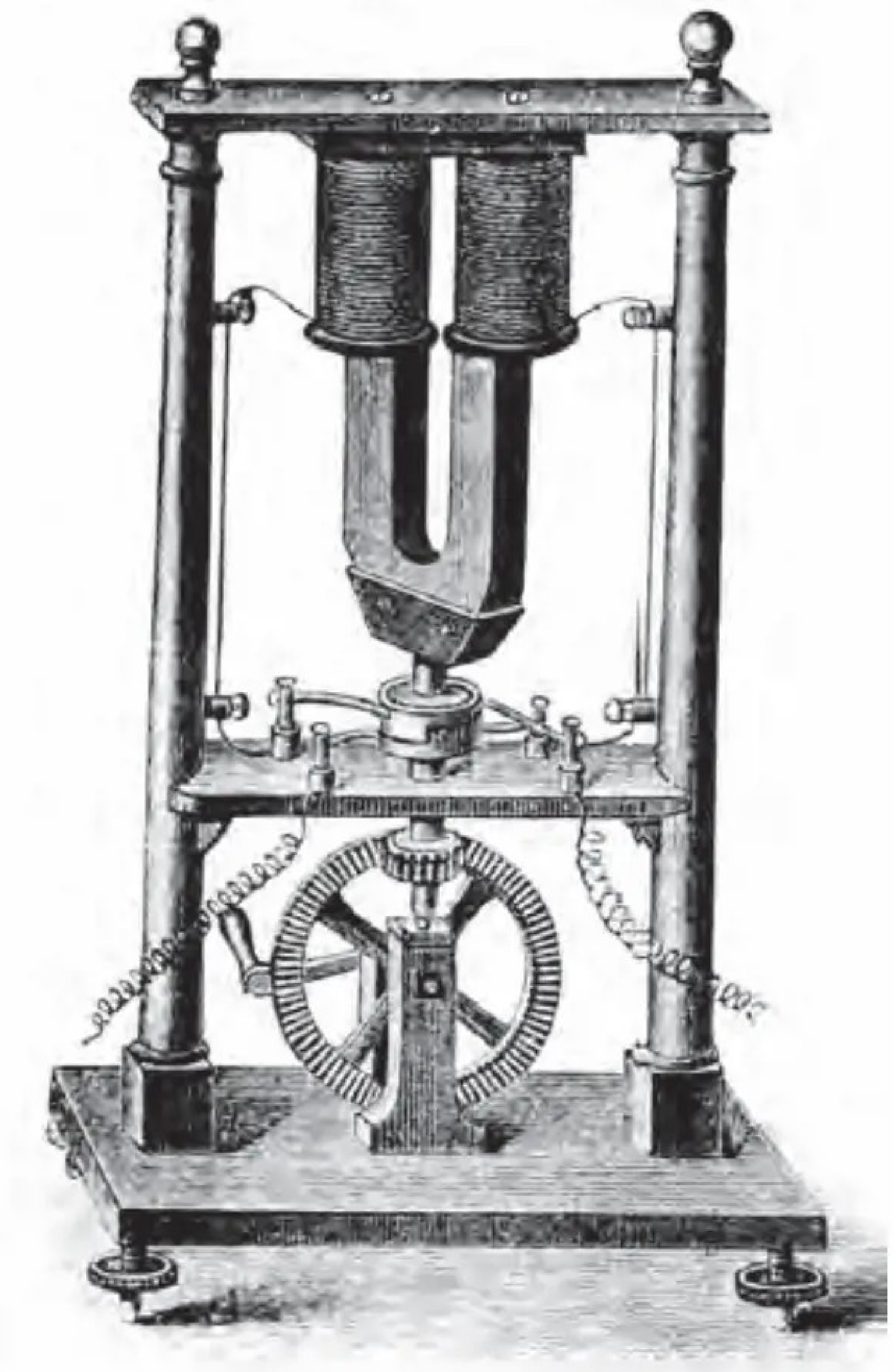


Fig.16: Pixii's dynamo. This later version produces pulsating direct current using the commutator below the magnet. ***Source:*** **https://w.wiki/78sZ**

inventor of telephony. His notes show he produced a device in 1856 that communicated voice via wires from his basement laboratory to his wife upstairs in their New York home. This included a type of dynamic microphone with a wire coil moving in response to sound within a magnetic field.

From 1856 to 1870, he developed more than 30 types of phone apparatus. In 1860, he publicly demonstrated his "teletrofono" in New York.

In 1870, he transmitted voice signals over more than 1.6km of wire. In 1871, he submitted a patent caveat to the US Patent Office. This document was essentially a notice of an intent to file a patent, but Meucci didn't have the money to submit a patent application.

Had he been able to, it might have stopped Alexander Graham Bell from receiving his telephone patent in 1876.

The invention of electric light

The story of the invention of electric light is far too long and complicated to fully cover here. We have included highlights, but if you want to know more, read "The Invention of the Electric Light" (236 pages) by B.J.G. van der Kooij, a free PDF download from pemag.au/link/abnh

Hippolyte Pixii
1808-1835

hand-cranked dynamo (electrical generator)

Invented a hand-cranked dynamo in 1832 based on Michael Faraday's discovery of electromagnetic induction. It produced an alternating current when a horseshoe (permanent) magnet passed over two iron cores – see Fig.16. At the time, DC was the preferred means of current for experiments.

Upon André-Marie Ampère's suggestion, a commutator to reverse the current direction every half turn was later added to produce pulsating direct current.

William George Armstrong
1810-1900

hydroelectric power station

He built the first hydroelectric power station (Fig.17) in 1870. It was the Burnfoot Power House at Cragside Estate, Rothbury, England and used a Siemens dynamo. He was titled 1st Baron Armstrong.

Alexander Bain
1810-1877

electric clock and facsimile machine

Patented an electric clock in 1841 with John Barwise. Its pendulum was driven by electromagnetic pulses.

It included a reference to an "earth battery" made of dissimilar metals, buried in the ground, as a power source.

He also patented a telegraph in 1843 that printed messages, an early form of the facsimile machine. The image to be transmitted had to be

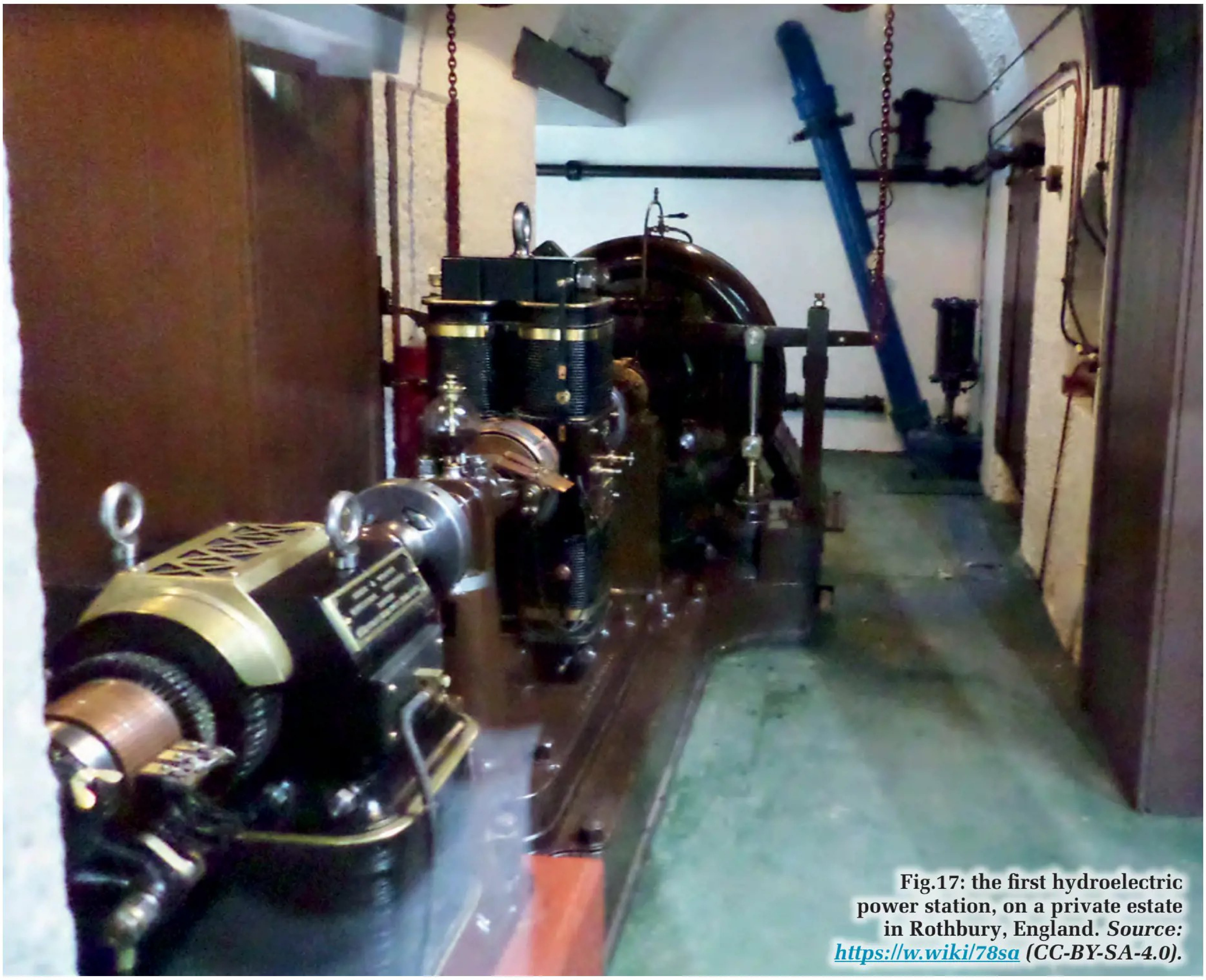


Fig.17: the first hydroelectric power station, on a private estate in Rothbury, England. ***Source:*** ***https://w.wiki/78sa*** ***(CC-BY-SA-4.0).***

Controversy over the invention of the telephone

You may notice many references in this article to various people who made telephone-related inventions.

The matter of who invented the telephone has been subject to considerable controversy, including the long-running court case in the USA from 1878 to 1901 involving A.G. Bell, Thomas Alva Edison, Elisha Gray, Emil Berliner, Amos Dolbear, J. W. McDonagh, G. B. Richmond, W. L. Voelker, J. H. Irwin and Francis Blake Jr.

Bell and the Bell Telephone Company eventually won that case, along with 600 other cases involving the invention of the telephone that went to trial. Another controversy involved Antonio Meucci. See https://w.wiki/78sh

formed by metal pins arranged on a rotating cylinder, so it was not very practical.

In 1846, he patented a printing telegraph that printed Morse Code on moving paper tape using chemical rather than mechanical means. He also devised a punched paper tape system for prerecorded messages that could be transmitted quickly. It could send 325 words per minute, compared to the Morse system at only 40 words per minute. Samuel Morse claimed patent infringement, and the system was not widely used.

Frederick Hale Holmes *1812-1875*
continuous current electro generators

Developed generators to power electric arc lighting in 1853. In 1856, he patented a magneto to power lighthouse arc lamps – see Fig.18.

Heinrich Geißler *1814-1879*
Geissler tube – early form of neon lighting

Invented the Geissler tube in 1857, a partially evacuated glass tube filled with various gases with a high voltage applied between two electrodes, causing the emission of light by fluorescence – see Fig.19. The technology was a predecessor to neon lighting.

Warren De la Rue *1815-1889*
incandescent light globe

He enclosed a platinum wire in an evacuated glass tube in 1840, creating an early incandescent light globe.

Giovanni Caselli *1815-1891*
fax machine

Invented the first practical fax machine in 1861, called the "pantelegraph" ("pan" meaning all in Greek). You can see a photo of it at: https://w.wiki/78ro

Ernst Werner von Siemens *1816-1892*
pointer telegraph, speakers, electric lifts etc

Invented the "pointer telegraph", in which a message was received by needles pointing at letters rather than Morse Code. In 1847, he established Telegraphen-Bauanstalt von Siemens & Halske to produce it (see the video at https://youtu.be/v8DZuT5c2CI). Siemens AG is still an innovative company today.

In 1874, he received US Patent 149,797 for a "Magneto-Electric Apparatus" for "obtaining the mechanical movement of an electrical coil from electrical currents transmitted through it". Although not intended as a loudspeaker, that is what became of the invention.

Alexander Bell was granted a patent for the telephone in 1876, which incorporated a moving-iron type loudspeaker. Subsequently, Siemens received German patent 2355 in 1877 for an improved speaker design with a moving coil transducer, a diaphragm as a sound radiator and a trumpet form as a cone. This was adapted by A. L. Thuras and E. C. Wente for use by the Bell System as a loudspeaker.

In 1880, Siemens built the world's first electric lift. He was the first to use gutta-percha latex to insulate telegraph cables, making the 1866 transatlantic telegraph cable possible. He also invented a practical dynamo and an electric railway. He also developed a process for galvanoplasty, plastics with gold or silver plating. The unit of conductivity, the **siemens (S)**, is named after him.

Scott de Martinville *1817-1879*
phono-autograph

Invented the earliest known device to record audio waveforms in 1857, the phonautograph (see Fig.20). However, these waveforms could not be played back.

In 2008, some waveform images from 1860 were digitised and converted back into sound, thus becoming the earliest known intelligible recording

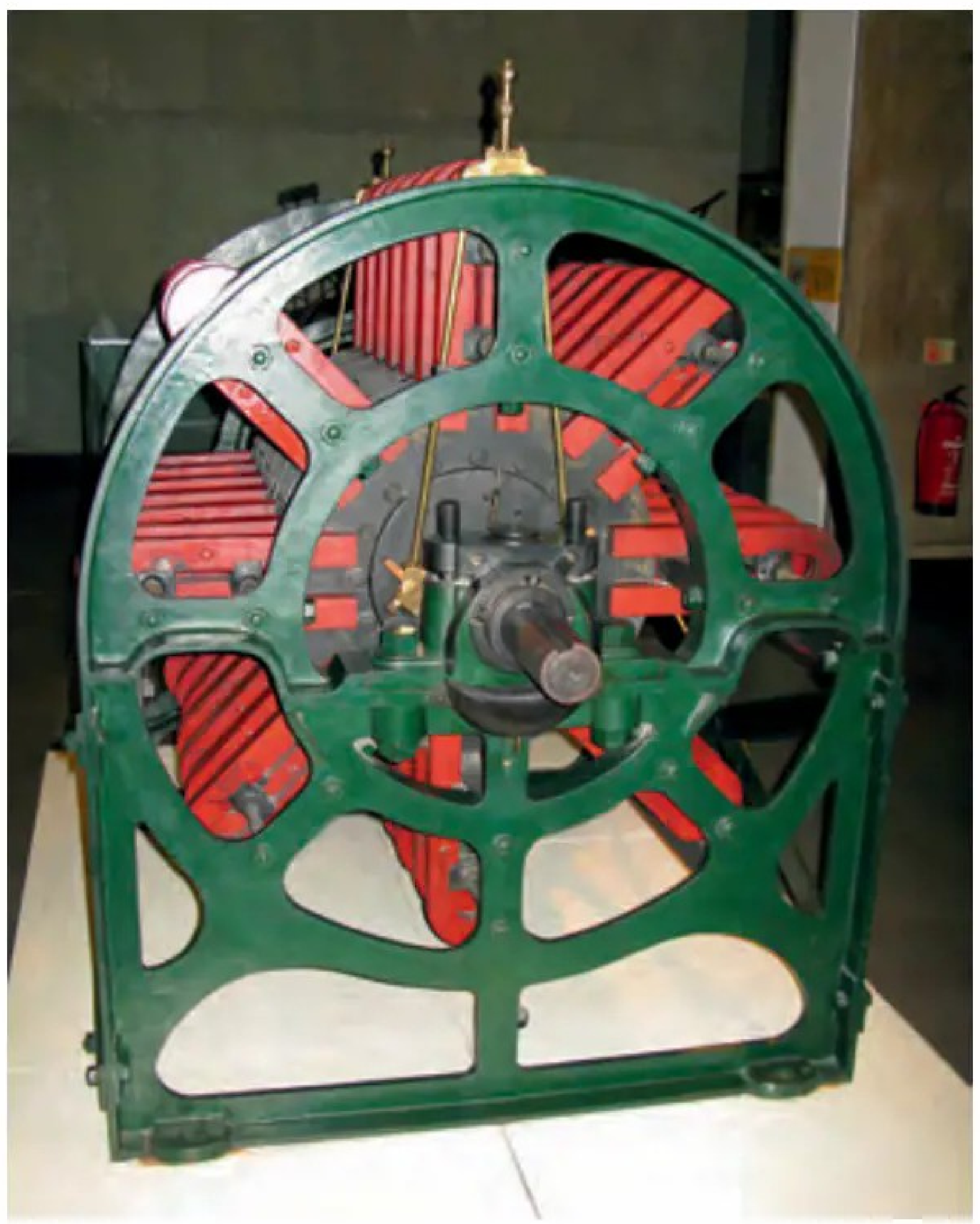


Fig.18: Frederick Hale Holmes' generator from Souter Lighthouse. *Source: https://w.wiki/7A2K (CC-BY-SA-4.0).*

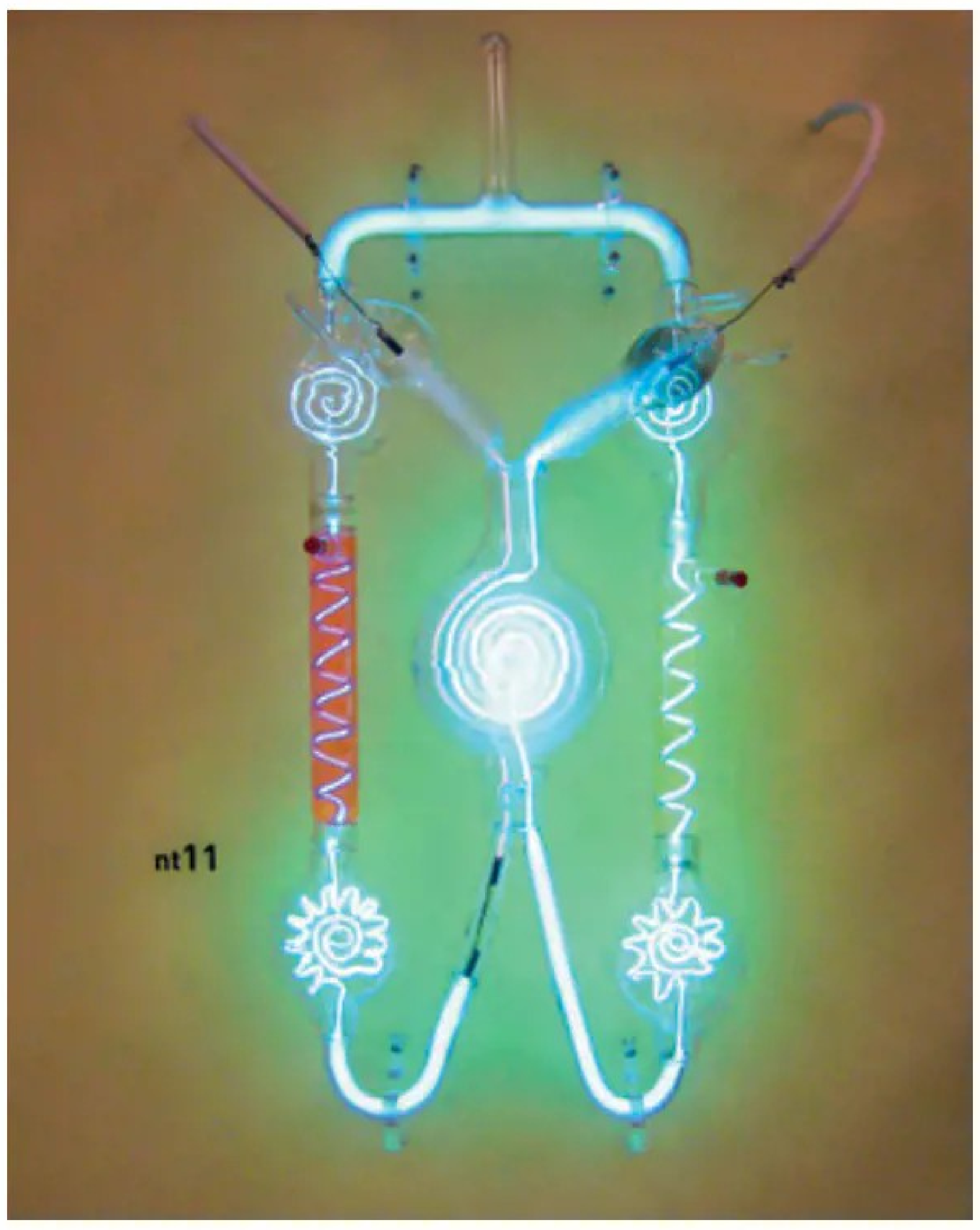


Fig.19: a Geissler tube in the form of a piece of modern art. *Source: https://w.wiki/78sf (CC-BY-2.0).*

Above: Ernst Werner von Siemens also invented the trolleybus, usually powered from overhead lines. *Source: https://w.wiki/7Arv*

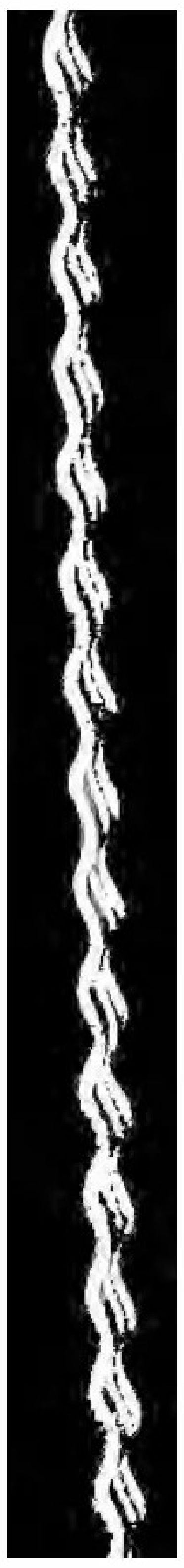


Fig.20 (right): a phonautograph visual recording, c.1859. *Source: https://w.wiki/78sb*

of a human voice. They were made 28 years before Thomas Edison's wax cylinder phonograph recordings.

James Prescott Joule 1818-1889

magnetostriction and Joule heating

An English physicist in the field of thermodynamics who established the concept of energy conservation, showing that heat, electricity and mechanical work were interchangeable. He discovered the relationship between current, resistance, and heat generation, which led to Joule's Law. The unit of energy, the **joule (J)**, is named after him.

He also did work in the area of magnetostriction. In 1843, he discovered the relationship between the heat dissipated by a resistor and the current through it. Resistance heating due to a current flow became known as Joule heating.

Léon Foucault 1819-1868

eddy currents

Credited with the discovery of eddy currents or "Foucault currents" in 1855, although these were first observed by Dominique François Jean Arago (see his entry last month).

Charles S. Bradley 1819-1888

three-phase generator

Built the first three-phase generator in the USA in 1887.

Moses Gerrish Farmer 1820-1893

duplex telegraphy, electric locomotives, bulbs

He investigated telluric currents, low-frequency currents that travel through the Earth or sea of natural or artificial origin.

In 1847, he demonstrated an electric locomotive that pulled two passengers on tracks, powered by a nitric acid battery. Along with William F. Channing in 1849, he demonstrated an improved electric fire alarm system in 1857.

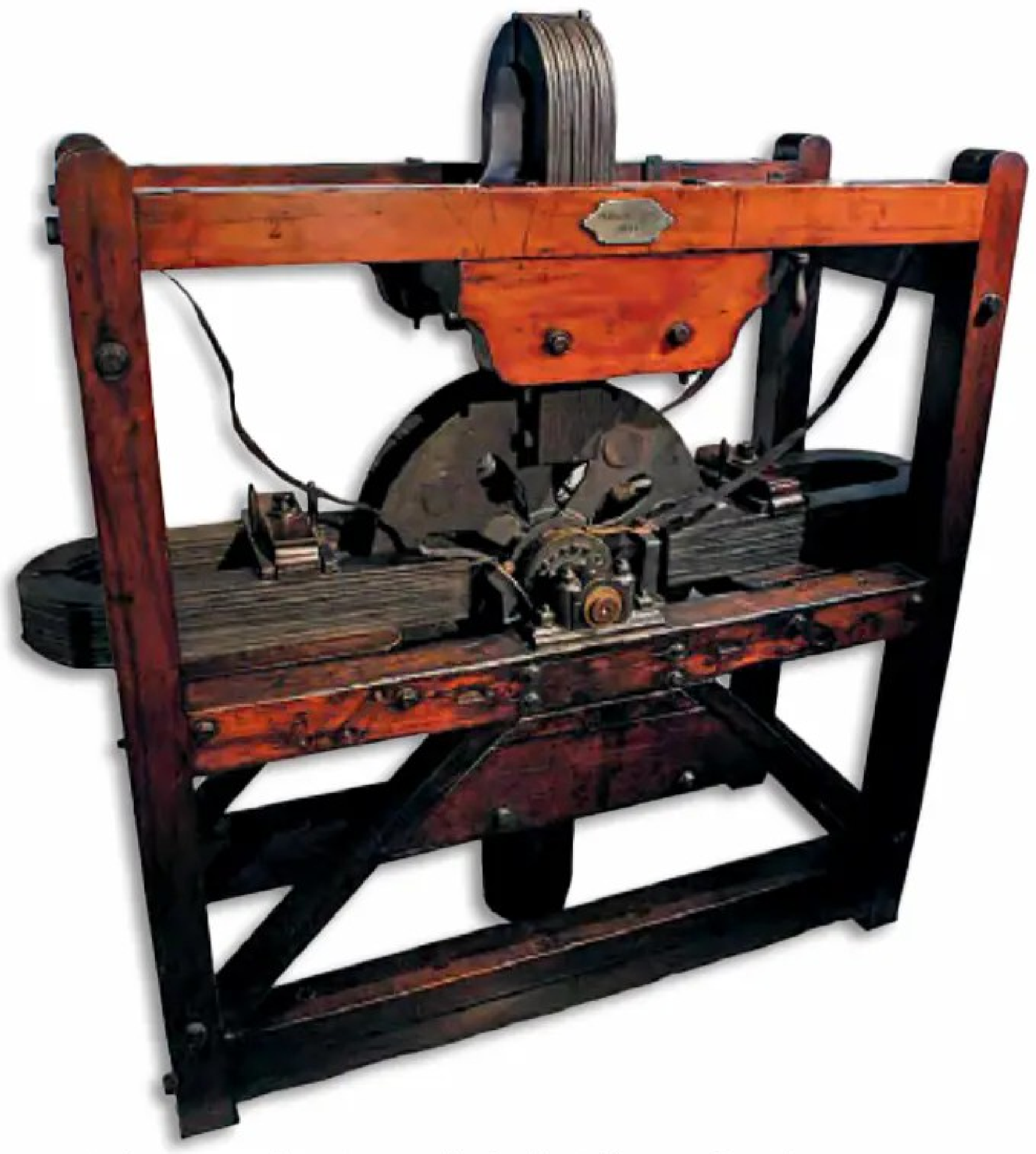


Fig.21: the Woolrich Electrical Generator, the first commercial generator. ***Source: https://w.wiki/78sc (CC-BY-SA-4.0).***

In 1852, he made repeaters for a telegraph system and, in 1853, patented a method to transmit four messages on one telegraph line simultaneously. In 1859, he co-created the self-exciting dynamo.

He invented a current regulator for his electric lamps in 1859. The "Wallace-Farmer 8 horsepower" (6kW) dynamo was used by Thomas Edison in early lighting demonstrations.

He made an incandescent light globe, also in 1859, using a platinum filament and lit his house with them in July 1859, the first house to be lit by electric lighting (not Joseph Swan's, as usually claimed).

John Stephen Woolrich 1820-1850

Woolrich Electrical Generator

He built the Woolrich Electrical Generator in 1844, the first generator used for an industrial process, commercial electroplating (see Fig.21). The voltage and current ratings are unknown.

Edmond Becquerel 1820-1891

photo-voltaic cell

He produced the first photovoltaic cell in 1839 (see Fig.22). When light was directed onto the device, voltage and current were produced. The photovoltaic effect is now known as the **Becquerel effect**.

John Wellington Starr 1822-1846

carbon & platinum filament incandescent globes

Filed patents in 1845 for two types of incandescent light globe, one based on a carbon filament and the other on a platinum filament. They were never commercialised. Nevertheless, the patent is considered the first important one on the road to a commercial electric light globe. There is quite an extensive story to John Starr and many uncertainties; see pemag.au/link/abn9

Hermann von Helmholtz 1821-1894

Helmholtz resonator and coil

Studied electrical resonance and invented the Helmholtz resonator during 1869-1871. He saw mechanics, heat, light, electricity and magnetism as a manifestation of a single force and published his ideas in "On the Conservation of Force" (in German) in 1877 – see pemag.au/link/abna

Helmholtz also invented the Helmholtz coil, which is two electromagnets arranged to provide a region with a close-to-uniform magnetic field.

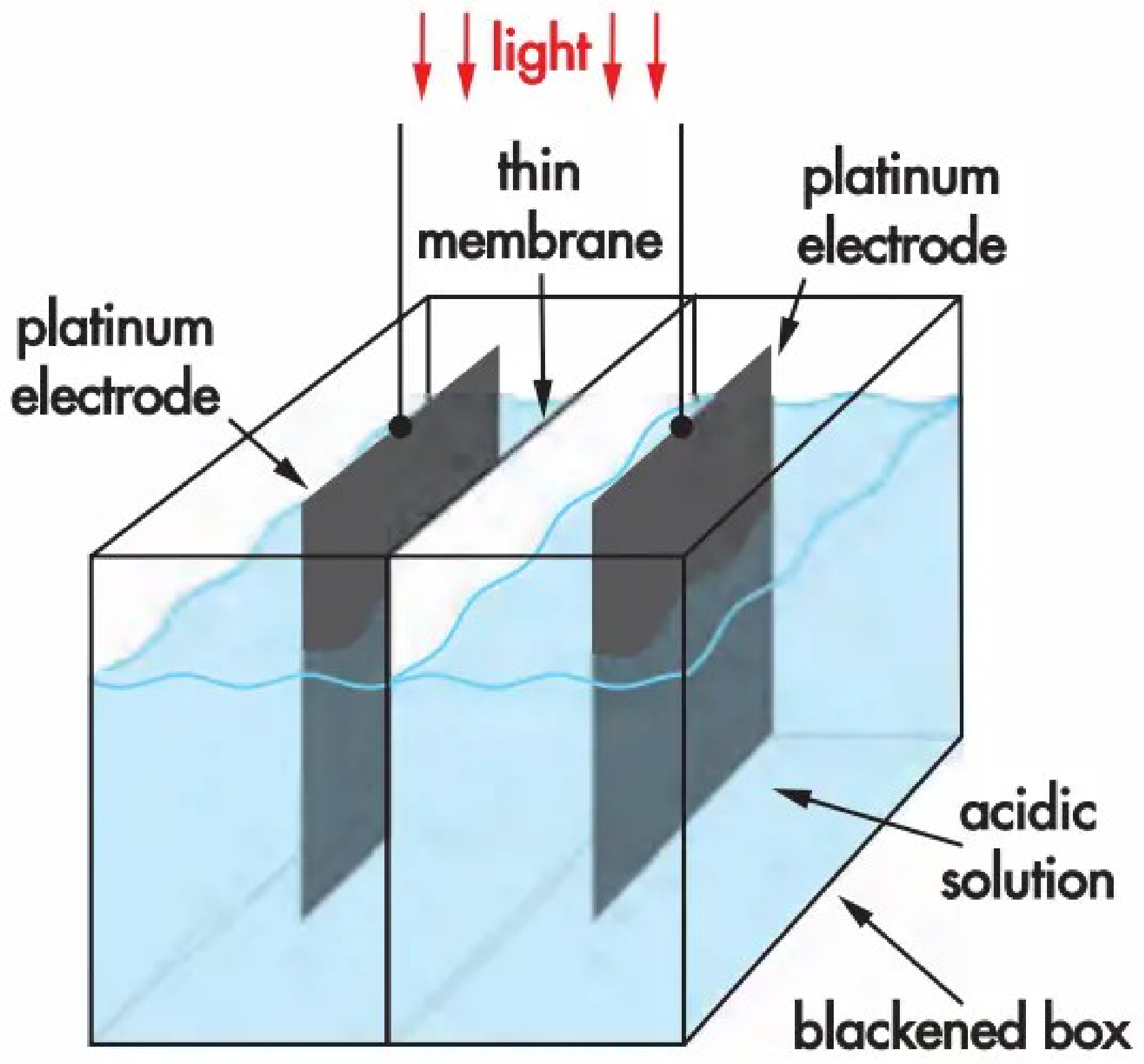


Fig.22: the first photovoltaic device from Edmond Becquerel. ***Source: www.pveducation.org/pvcdrom/manufacturing-si-cells/first-photovoltaic-devices***

A Helmholtz resonator is an enclosed volume with a neck that resonates at a specific frequency. They are incorporated in some car exhaust systems to eliminate noise at certain frequencies, and this phenomenon is also the cause of 'wind throb' in a car with open windows at certain speeds. See the video titled "How to build a Helmholtz Resonator DIY" at **https://youtu.be/JUsyeBkNVEI**

Lord Kelvin 1824-1907

bandwidth, mirror galvanometer etc

Also known as William Thomson, developed and patented a system for submarine telegraph cable in 1855, with calculations of the achievable data rate in relation to cable diameter and copper purity (bandwidth). He was also awarded patents for a mirror galvanometer (1858) and "siphon recorder" (1867) to record messages.

Lord Kelvin resting on a binnacle (housing for a ship's compass) while holding a marine azimuth mirror. ***Source: https://w.wiki/7Arz***

Thomson's submarine telegraph system could send one character every 3.5 seconds. He also significantly contributed to thermodynamics; the absolute temperature unit **Kelvin (K)** is named after him. He invented the Kelvin balance that allowed the unit of current (the ampere) to be precisely defined.

Gustav Robert Kirchhoff 1824-1887
Kirchhoff's circuit laws

He made significant contributions in the fields of electrical circuits, spectroscopy and the emission of black-body radiation by heated objects. **Kirchhoff's circuit laws** from 1845 are foundational to electrical engineering and physics. They allow an electrical network (circuit) to be analysed to determine the expected currents and voltages.

Zénobe Gramme 1826-1901
Gramme machine (DC dynamo)

In partnership with Hippolyte Fontaine, they built and manufactured an improved DC dynamo around 1873, called the Gramme machine, which produced smoother DC and higher voltages than prior machines. The duo also worked on other electrical devices.

In 1873, he and Fontaine discovered that if the dynamo were connected to a DC supply, it would work as a much more powerful electric motor than any others at the time, which were of no practical use.

Willoughby Smith 1828-1891
photo-conductivity

Discovered photoconductivity in 1873 (when a material becomes more conductive upon exposure to light) in selenium.

Sir Joseph Wilson Swan 1828-1914
first successful light globe

Started experimenting with incandescent light globes in 1860, but was hampered by the lack of a good vacuum pump and a suitable power supply. In 1878-1879 he demonstrated the first incandescent light with a carbon filament in an evacuated globe, and he is regarded as the inventor of the first successful globe (see Fig.23).

His house was claimed to be the first house to have electric lighting, but Moses Gerrish Farmer's was likely first (see page 57).

In 1881, he installed 1200 light globes in the Savoy Theatre in London, the first public building to have them. They were powered by an 88kW generator. Thomas Edison independently developed the light globe, and both men obtained patents in 1880.

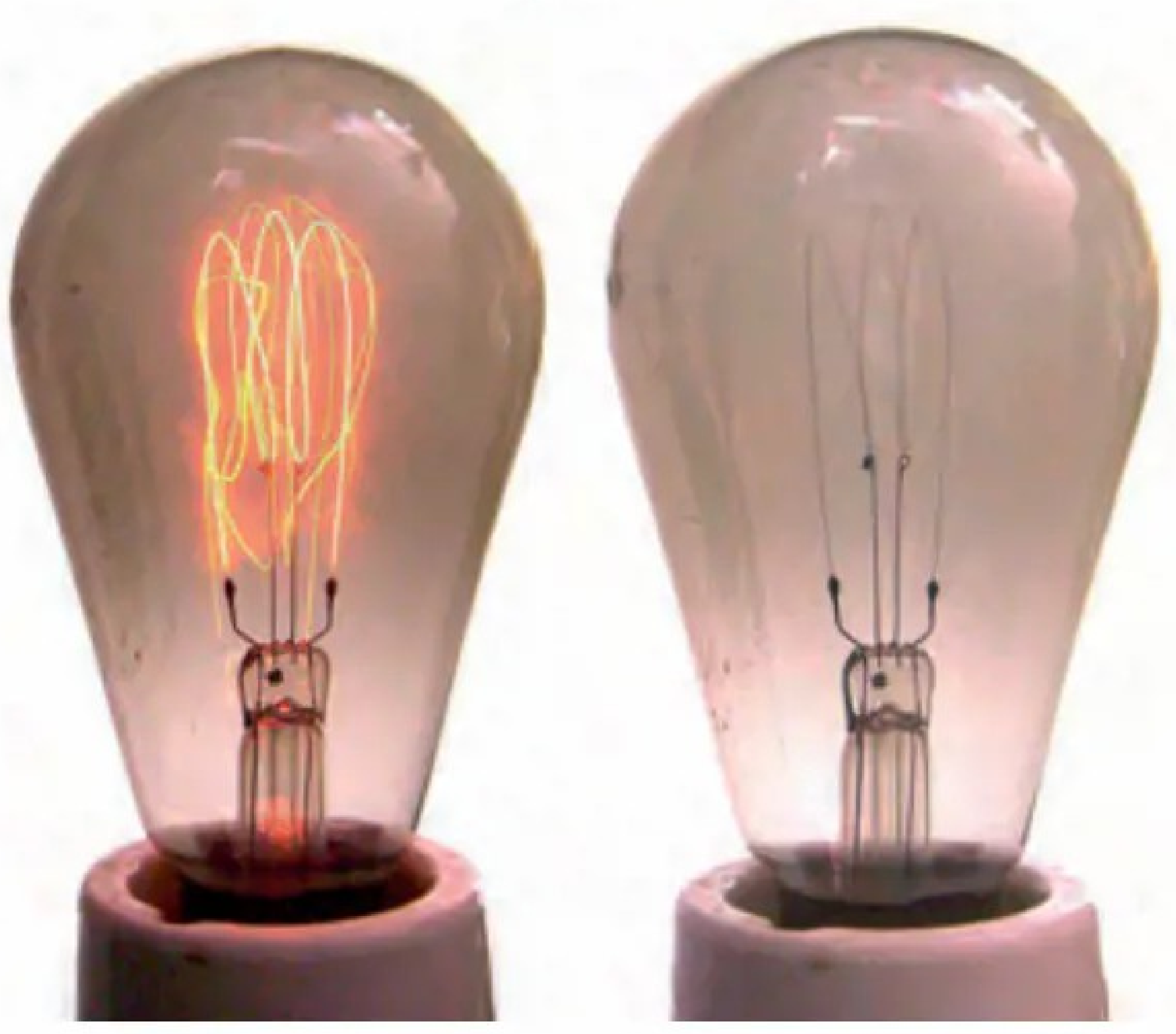


Fig.23: These carbon filament bulbs show the blackening effect. This is due to the evaporated carbon condensing on the inner surface of the bulb. *Source:* https://w.wiki/7As8

Swan sued Edison. This led to a joint company being formed in Great Britain in 1883, the Edison & Swan United Electric Light Company ("Ediswan"), to exploit the inventions. Edison and Swan produced successful light globes, but there were many ideas for globes before them, starting with Volta.

David Edward Hughes 1830-1900
printing telegraph and microphone

Developed a printing telegraph system in 1855. In 1878, he described electronic carbon-powder-based sound pickups called "transmitters", then being developed for telephones. He demonstrated how they worked, superseding the prevailing theory of the time and coining the term "microphone".

He developed a type of microphone but never patented it, thinking the work should be available for the benefit of all. In 1879, he likely detected radio waves before Heinrich Rudolf Hertz did in 1887/1888, but attributed the phenomena to electromagnetic induction rather than radio waves.

James Clerk Maxwell 1831-1879
Maxwell's equations

Discovered that electricity, magnetism and light were different manifestations of the same thing. He produced **Maxwell's equations** in 1861-62, which are the basis of electrical circuit and light theory. They explain how electric and magnetic fields relate. Oliver Heaviside produced the modern form (the Maxwell-Heaviside equations).

His work combining all previous observations, experiments and equations into a consistent electromagnetic theory set the foundation for much of 20th-century physics and led to the era of modern physics.

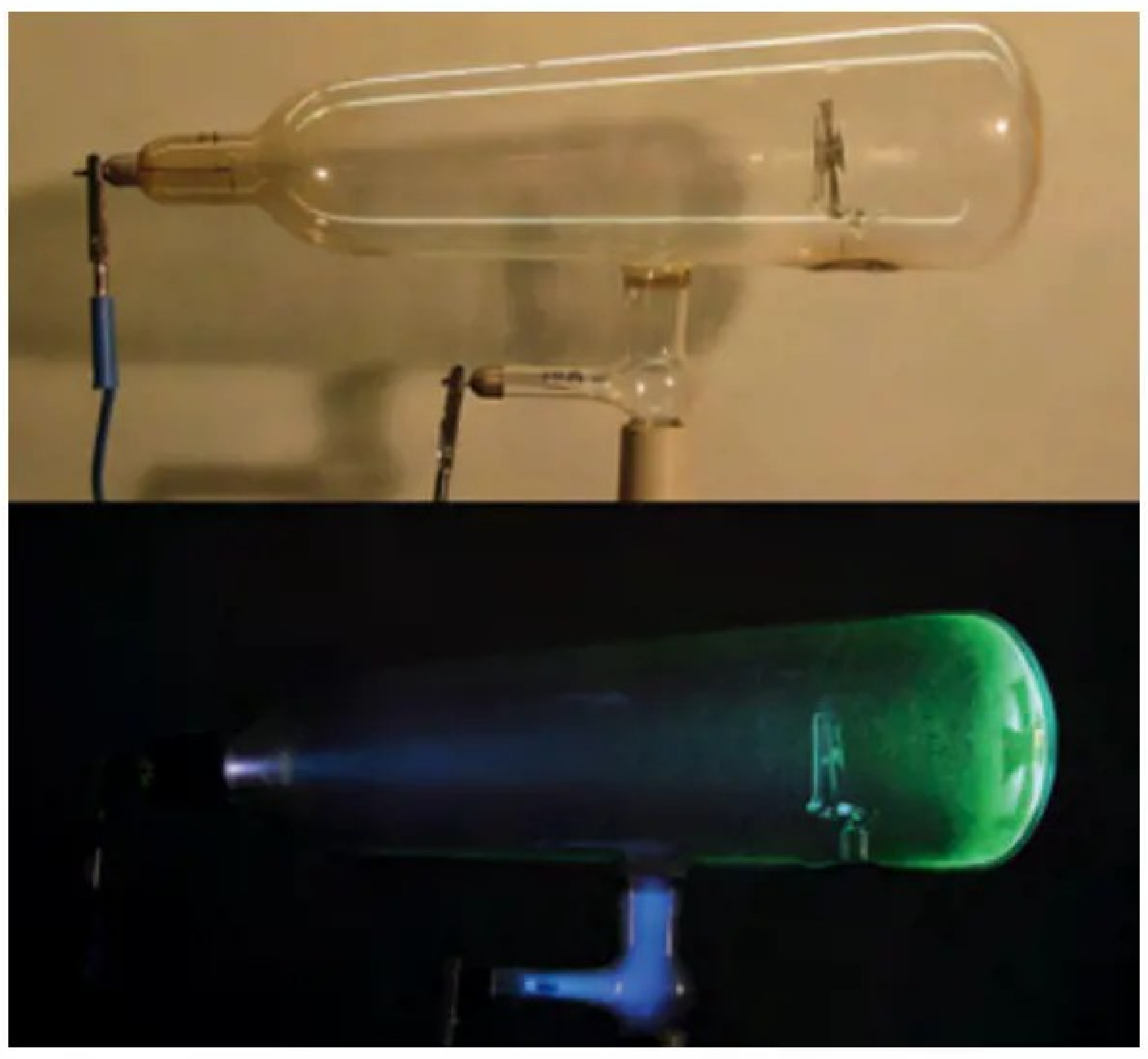


Fig.24: a Crookes tube, the basis of the cathode ray tube (CRT). *Source: D-Kuru/Wikimedia Commons –* https://w.wiki/7BiD

Henry Woodward & Matthew Evans
incandescent light globe

Together they obtained a Canadian patent in 1874, then US Patent 181,613 in 1876 for an incandescent light globe that used a carbon filament in a nitrogen-filled enclosure. They did not have enough money to develop their invention, so they sold the patents to Thomas Edison in 1879.

Sir William Crookes 1832-1919
Crookes tube – the basis of X-ray tubes

Invented the Crookes tube (Fig.24) around 1869-1875. It is a partially evacuated glass tube with an anode at one end and a cold cathode at the other that produces cathode rays. The shape of the anode causes a shadow to be projected by the cathode rays (electrons), some of which are blocked by the shape, while others that pass to the outside.

It is the basis of X-ray tubes and the cathode ray tube (CRT) as was commonly used for TVs, computer screens, radar displays and oscilloscopes. Some CRTs used heated cathodes.

John Dixon Gibbs 1834-1912
power transformer

With Lucien Gaulard, he demonstrated a power transformer in 1881 and obtained US patent 351,589 in 1886. While transformers were not a new idea, this was the first that could handle power at industrial levels.

Johann Philipp Reis 1834-1874
Reis telephone and speaker

Constructed a type of telephone in 1861 with a range of 100m (Fig.26). It incorporated a microphone based upon a parchment diaphragm that altered the electrical resistance between two contacts when it vibrated, one of which was dipped in a drop of mercury.

He also made a speaker that produced reasonable but weak sound, it was based on magnetostriction (ferromagnetic materials changing their shape when subjected to a magnetic field). Reis' device could not reproduce speech intelligibly, so his patent was not upheld in a dispute with Alexander Graham Bell.

However, David Edward Hughes later reported good results with the Reis telephone. Around 1947, the Reis device was tested by the British company STC, which confirmed it could transmit and receive speech, albeit faintly.

The patent was partly invalidated because of a mistake in describing how the microphone worked; Reis said it worked by making and breaking electrical contact when it actually varied the resistance.

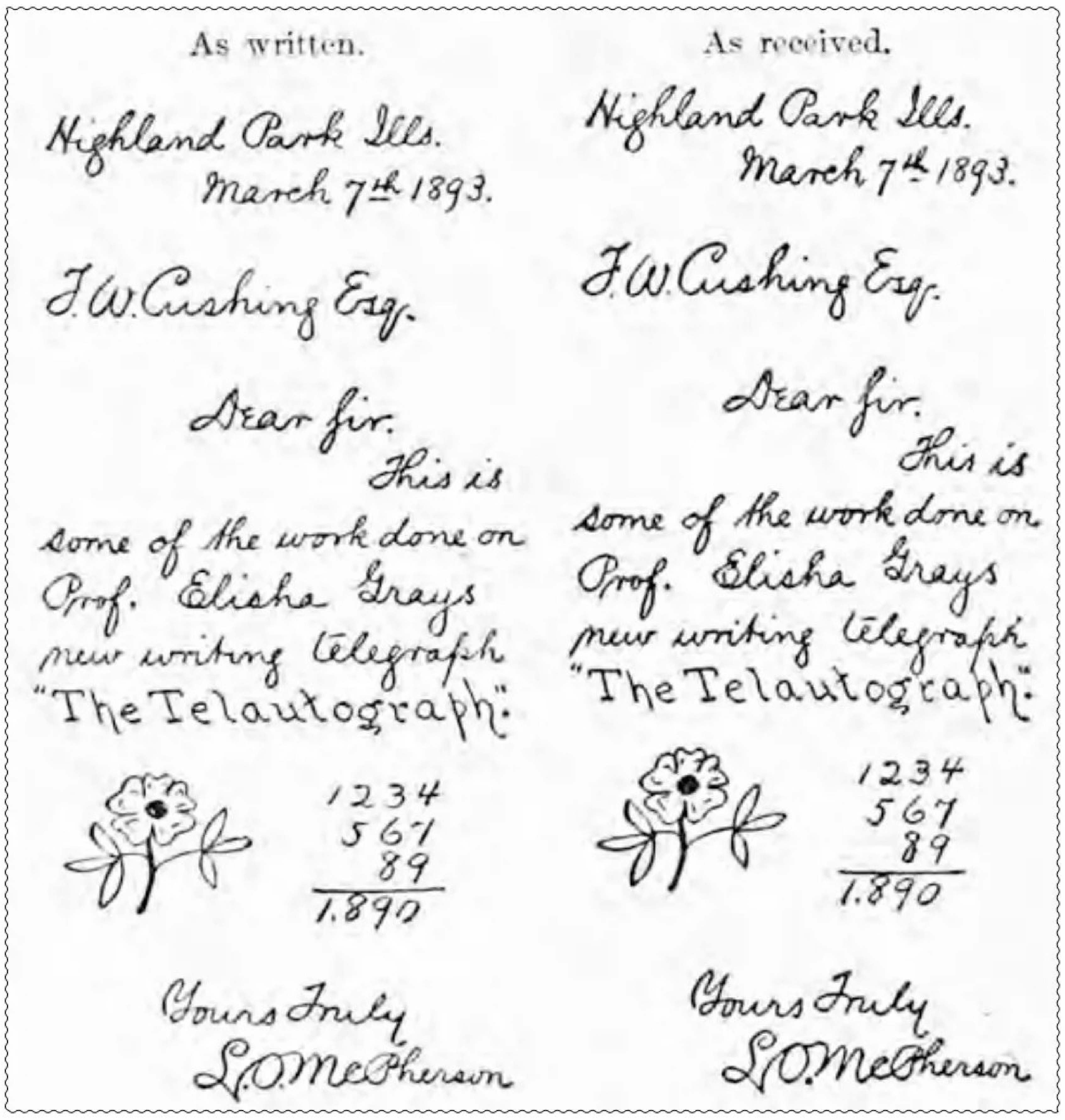
Elisha Gray 1835-1901

Musical Telegraph, telephone etc

Invented an improved printing telegraph in 1872 (US patent 132,907). He also invented a "Musical Telegraph" that transmitted single musical tones over a telegraph link in 1874 (US patent 173,618). Oscillating steel reeds controlled by electromagnets produced the tones. See the video titled "Elisha Gray's Musical Telegraph" at https://youtu.be/YxxsTdjT7PA

Gray secretly built a prototype telephone in 1876. Alexander Graham Bell's lawyer got to the patent office shortly before Gray's lawyer; thus, Bell got credit for the invention. The true inventor of the telephone is still hotly contested. Gray is, however, known for inventing one of the first electric musical instruments (Fig.27).

In 1887, he invented the telautograph, a precursor to the fax machine, although he is thought to have conceived the idea as early as 1874. He patented it in 1888 (US patent 386,814). A user's handwriting was transmitted using a stylus attached to a mechanism that transmitted the stylus' coordinates over a two-wire telegraph circuit (see Fig.25). The system became very popular.



As written.

Highland Park Ills.
March 7th 1893.

J.W. Cushing Esq.

Dear Sir.
This is
some of the work done on
Prof. Elisha Grays
new writing telegraph
"The Telautograph".

1234
567
89
1.890

Yours Truly
L.O. McPherson

As received.

Highland Park Ills.
March 7th 1893.

J.W. Cushing Esq.

Dear Sir.
This is
some of the work done on
Prof. Elisha Grays
new writing telegraph
"The Telautograph".

1234
567
89
1.890

Yours Truly
L.O. McPherson

Fig.25: the original writing and received copy on the Elisha Gray telautograph. *Source: Popular Science Monthly, Volume 44, 1893-94.*

A telautograph can be seen in operation in the 1956 movie *Earth VS The Flying Saucers* on YouTube: https://youtu.be/JCdnv3AP0eM?t=3683

William Grylls Adams 1836-1915

selenium produced an electric current

Together with his student Richard Evan Day, they discovered that a platinum/selenium junction produced a current in 1876.

Oberlin Smith 1840-1926

recording sound

He proposed a method for recording sound by magnetic means in 1888. A thread such as cotton was coated with

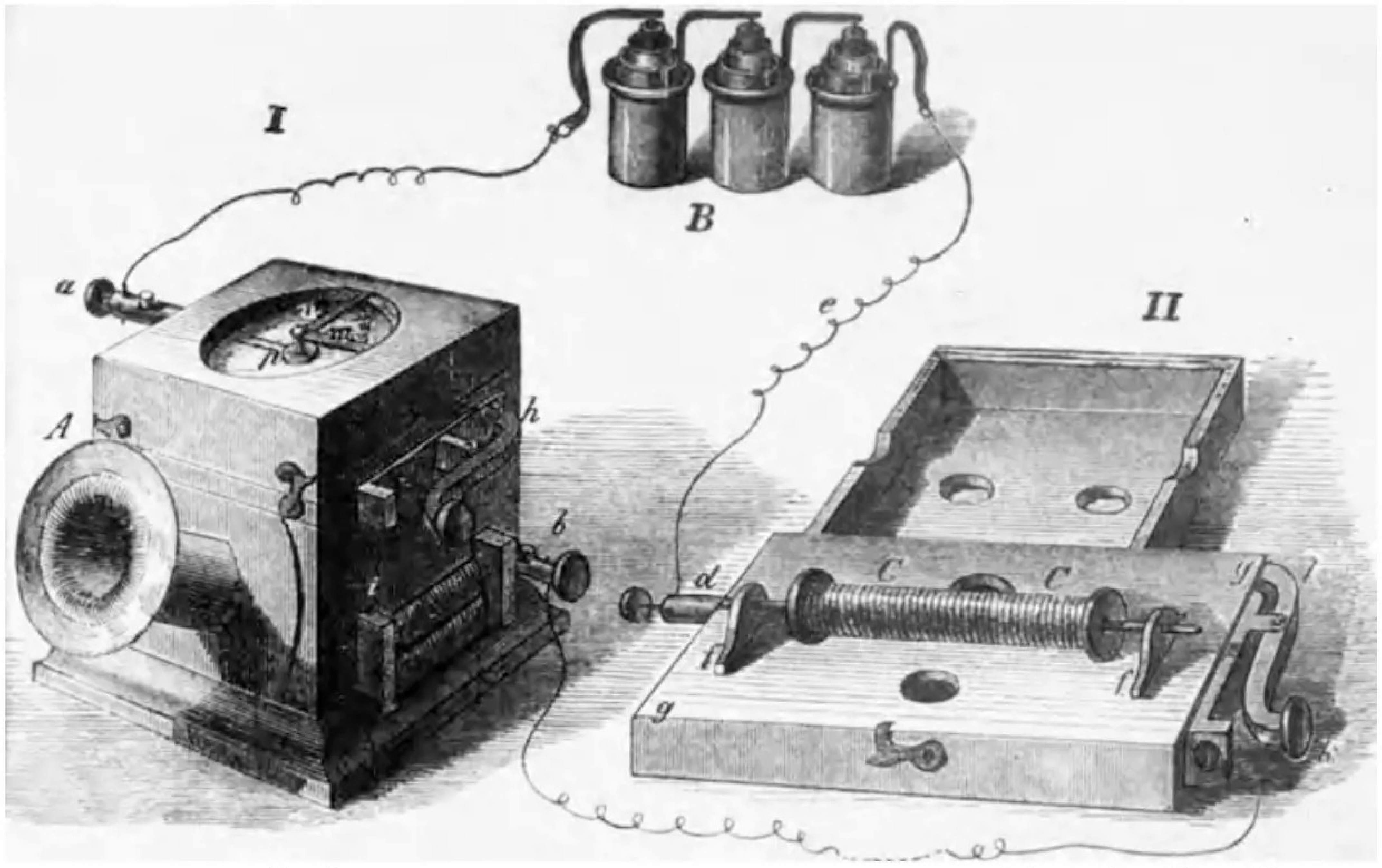


Fig.26: a Reis telephone consists of a transmitter, receiver (C) and a glass dome, all powered by a battery (B).

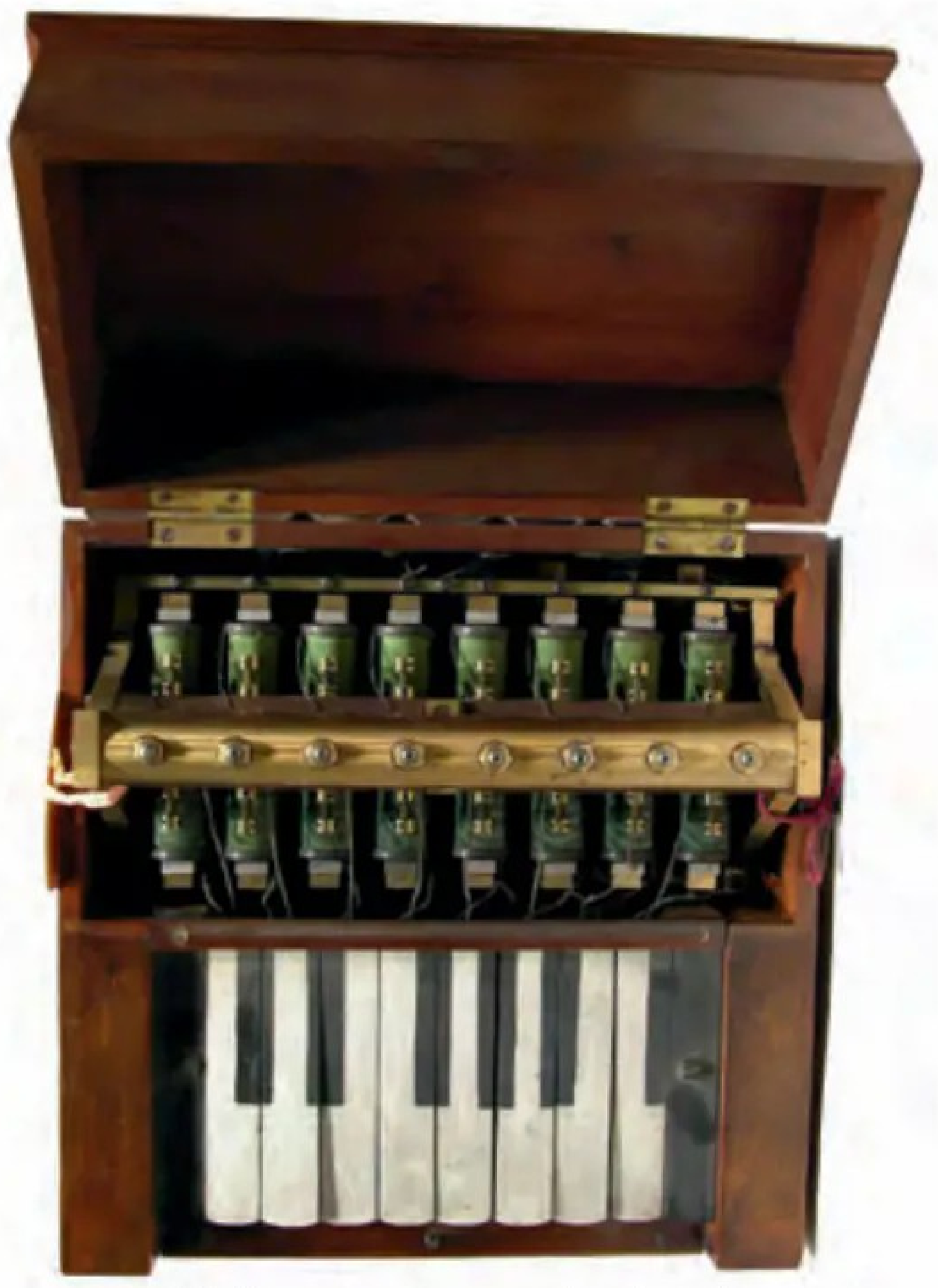


Fig.27: Elisha Gray's Musical Telegraph from 1876. *Source: https://americanhistory.si.edu/collections/search/object/nmah_703475*

or contained a magnetic powder or short lengths of fine wire, which were then magnetised by the current from a microphone source.

His ideas were implemented by Valdemar Poulsen (see his entry next month) but it is unknown whether Poulsen was familiar with Smith's work.

Sir Hiram Maxim 1840-1916
electric lamps

While famous for designing weapons, he also made significant contributions to the development of electric lighting, including improved methods of carbonising and manufacturing filaments for electric lamps.

John William Strutt 1842-1919
Rayleigh scattering & waveguides

Also known as Lord Rayleigh, made the first theoretical analysis of electromagnetic waves in a metal cylinder (waveguide) in 1897. He discovered what is now known as Rayleigh scattering, along with many other discoveries.

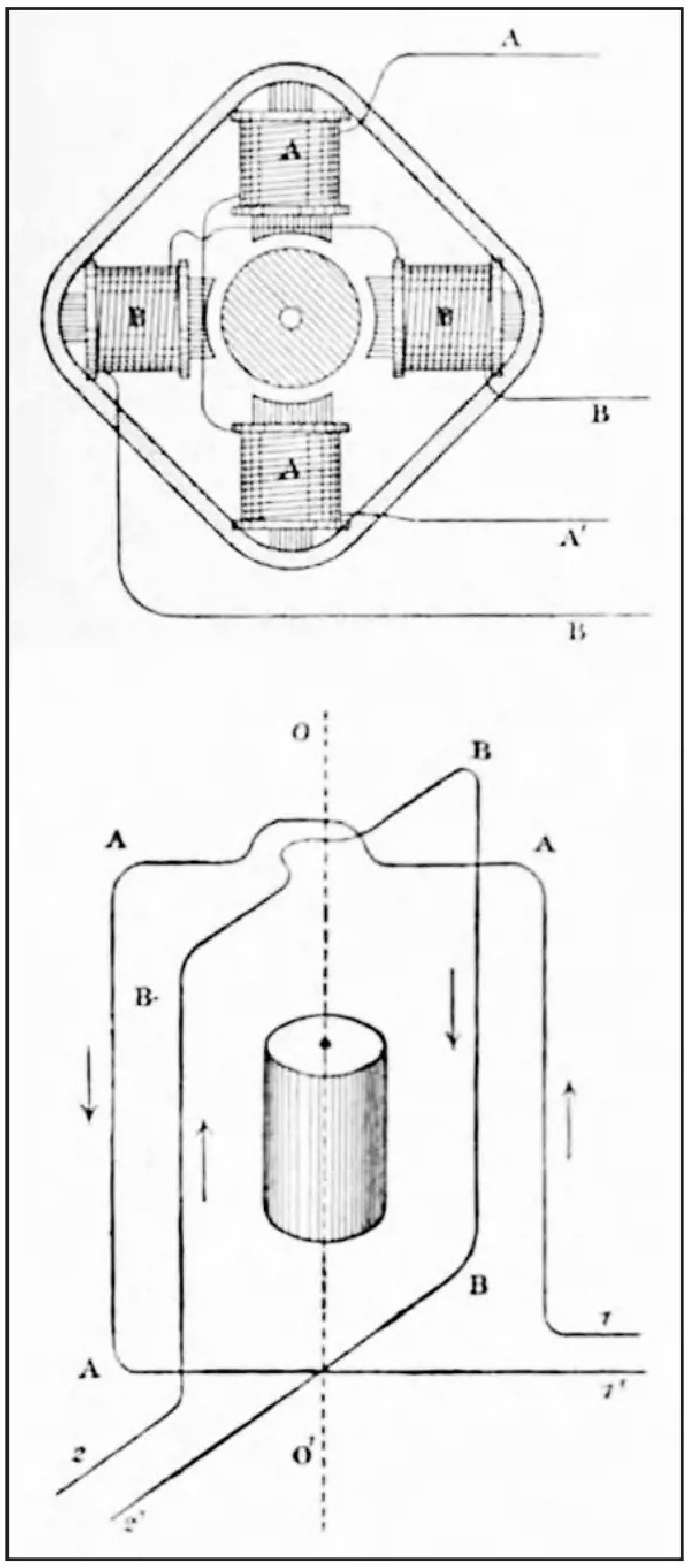


Fig.28: the world's first AC motor from 1895 by Ferraris. *Source: https://w.wiki/78se*

Nikolay Benardos & Stanisław Olszewski
arc welding

They used a carbon arc to soften metals to a plastic state and, in 1881, demonstrated the first practical arc welding.

Édouard Branly 1844-1940
coherer (radio signal detector)

Invented the coherer, the first detector of radio signals in 1890, based upon the work of Onesti (see his entry next month). It consisted of iron filings in an insulating tube with two electrodes.

Tivadar Puskás de Ditró 1844-1893
telephone and multiplex switchboard

Invented the telephone switchboard in 1876. The first one was built by the Bell Telephone Company in 1877. In 1887, he invented the multiplex switchboard for more efficient resource sharing.

Augustus Floyd Delafield 1845-1927
homopolar motor

He received US patent 278,516 in 1883 for a "dynamo-electric machine" based on Faraday's homopolar motor design. The video titled "The Homopolar Generator" at https://youtu.be/cQ5Ueouk_VY shows how it works.

Sir Mark Oliphant built a famous homopolar generator at Australian National University (ANU). It was one of the largest ever built and could deliver currents of 2MA. It operated from 1962 to 1986 and was designed to produce extremely high current pulses for applications such as rail guns.

Wilhelm Conrad Röntgen 1845-1923
X-rays

Was investigating vacuum tube equipment produced by others in 1895 when he discovered X-rays. He was performing experiments with a Crookes tube and fortuitously had some barium platinocyanide on his hand, a chemical known to fluoresce in UV light. He noticed it glowing out of the corner of his eye, an area of the eye that's very sensitive to light.

He had the barium platinocyanide because of experiments he was doing with a Lenard window tube, a Crookes tube with a thin window to allow some electrons to escape into the atmosphere.

Alexander Lodygin 1847-1923
carbon and metal filament lamps

Later known as Alexandre de Lodyguine, obtained Russian and European patents in 1872 for a carbon filament lamp. In the 1890s, he invented some metal filament lamps and obtained US patent 575,002 for a tungsten filament lamp. He sold the patent to General Electric in 1906.

Pavel Yablochkov 1847-1894
carbon arc lamp

Invented a kind of carbon arc lamp in 1876 called the "Yablochkov candle". It would run for about two hours and could only be used once; it needed a large power source, produced a buzzing sound, UV rays, carbon monoxide and was a fire hazard.

To power his lamps, Yablochkov invented a type of transformer based on Faraday's discovery of induction to supply the required AC voltage for the lamps. The use of transformers to supply different voltages later became the basis of AC power distribution systems.

Galileo Ferraris 1847-1897
polyphase alternator and induction motor

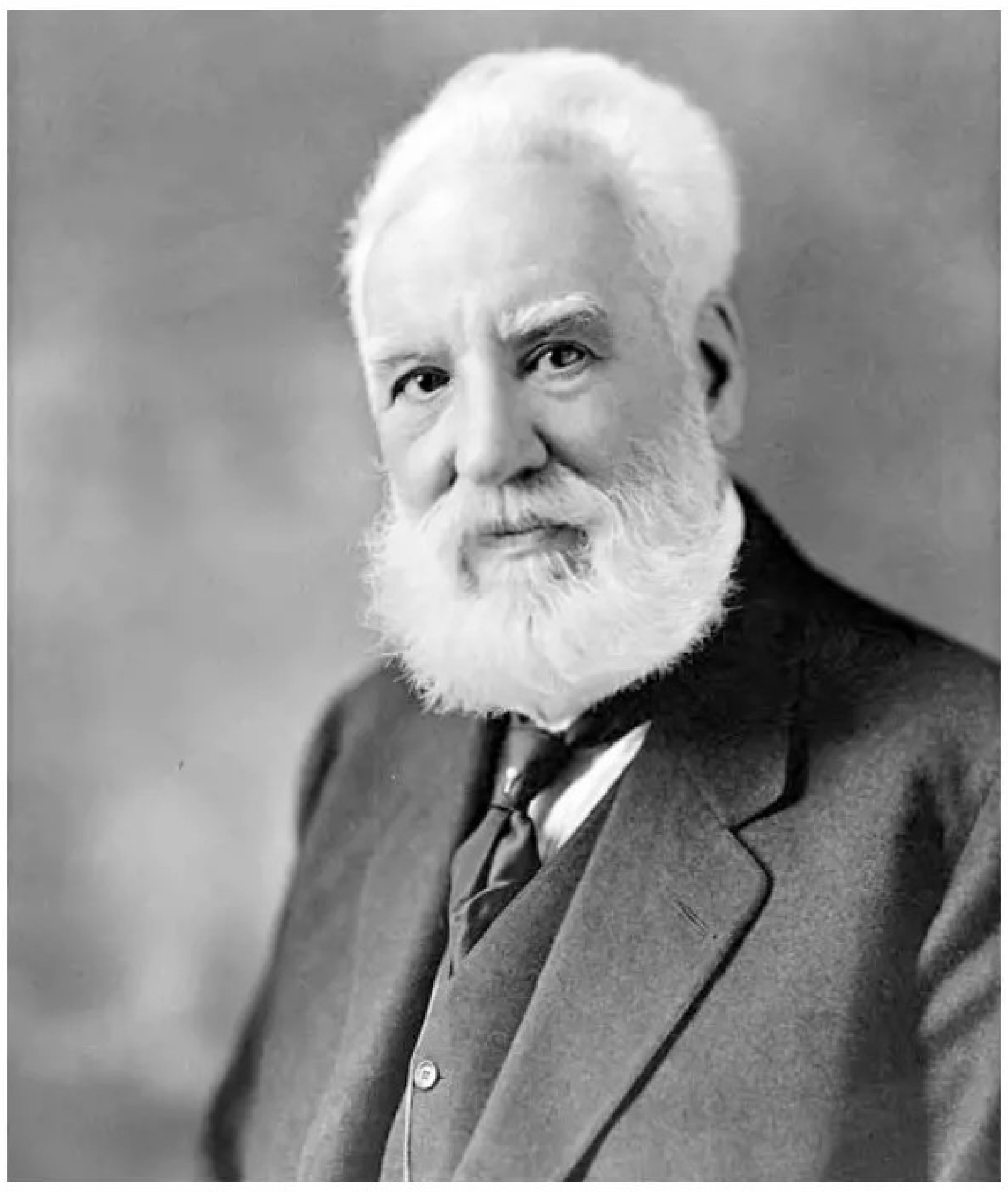
He worked in the area of rotary magnetic fields in 1885. Such fields can be provided by a polyphase alternating current driving a system of coils or a single phase with windings arranged in a particular manner.

His work led to the development of the polyphase alternator (effectively an AC motor operating in reverse) and the first induction (asynchronous) motor (Fig.28), but he did not patent it. He published his research on motors in 1888, just two months before Nikola Tesla obtained a patent for such motors.

The invention of the polyphase alternator was a crucial event in the history of electrification.

Alessandro Cruto 1847-1908
high-purity graphite light globe filaments

Started experimenting with light globe filaments in 1880 and devised a



Alexander Bell also co-founded AT&T. *Source: https://w.wiki/7AsL*

process of making high-purity graphite filament, which he demonstrated at the Electricity Expo in Munich in 1882.

This filament was more efficient than that used in Edison's globe and produced a white light, unlike Edison's yellow light. Also, it lasted for 500 hours, while Edison's original version only lasted 40 hours.

He established a factory in Alpigano, Italy, producing 1000 globes per day. After disagreements, he resigned from the factory and, after many changes of hands, it was acquired by Philips in 1927.

Alexander Graham Bell 1847-1922

telephone, photophone etc

Bell is most famous for his work in developing telephony. In 1875, he developed an acoustic telegraph to send multiple telegraph messages on one line (ie, a multiplexing method). He filed US patent 174,465 in 1876 for the telephone, slightly before Elisha Gray (as noted earlier).

Bell got his "instrument" (as he called it) to work for voice only three days after he got the patent, using a liquid transmitter (microphone) of Gray's design; his first famous words on the device were to his assistant, Thomas Watson, "Mr Watson, come here, I want to see you".

Despite his achievements with the telephone, Bell regarded his greatest achievement as the photophone in 1880. This enabled voice transmission on a modulated light beam that travelled 213m in one experiment.

It had no real application until the invention of the laser (1960) and the optical fibre (1965) for optical transmission of information. It was jointly invented with his assistant Charles Sumner Tainter.

Some of the oldest audio recordings

A collection of early sound recordings and associated links are available at pemag.au/link/abni

The following link is to a recording made by Alexander Graham Bell in 1885. It was recovered optically by 3D imaging the grooves of the wax disc recording: pemag.au/link/abnj

You can also see a video where the author searched through old texts to find sound representations and digitally converted them to the original sounds at https://youtu.be/TESkh3hX5oM

Thomas Alva Edison 1847-1931

microphones, acoustic telegraphy, fuse etc

Edison was a prolific inventor and entrepreneur.

In 1873, he demonstrated the varying resistance of carbon grains in response to pressure and built a rheostat based on that idea, but abandoned it due to sensitivity to vibration. It was useless for its intended purpose in telegraphy but came in handy later for carbon powder microphones, which he tested in 1876.

In 1875, he performed experiments in acoustic telegraphy, the name for multiplexing messages on telegraph lines, receiving US patent 182,996 in 1876.

He filed for US patents 474,230, 474,231 & 474,232 for a "Speaking telegraph" in 1877, awarded in 1892. The patents took so long to be granted due to the competing claims of Alexander Graham Bell, Emile Berliner, Elisha Gray, Amos Dolbear, J.W. McDonagh, G.B. Richmond, W.L.W. Voeker, J.H. Irwin, Francis Blake Jr and others.

In 1877, he invented a phonograph. The device recorded on tin foil and could only be used a few times; nevertheless, he gained fame for it. In 1878, he demonstrated the machine in Washington, DC and was celebrated as a genius. He received US patents 200,521 and 227,679 for it in 1878 and 1880, respectively.

In 1878, he established the Edison Electric Light Company and said, "We will make electricity so cheap that only the rich will burn candles". In 1879, he filed and, in 1880, received US patent 223,898 for an "Electric-lamp". In 1880, he established the Edison Illuminating Company for electricity distribution in New York and, in 1882, opened the Pearl Street Station (600kW, 110V DC).

In the 1880s and 1890s, there was the "War of the Currents", the debate about whether electricity distribution systems should be DC or AC. Edison supported DC and saw AC as dangerous and unworkable. Edison invented a fuse in 1890 to protect his electrical distribution system.

Next month

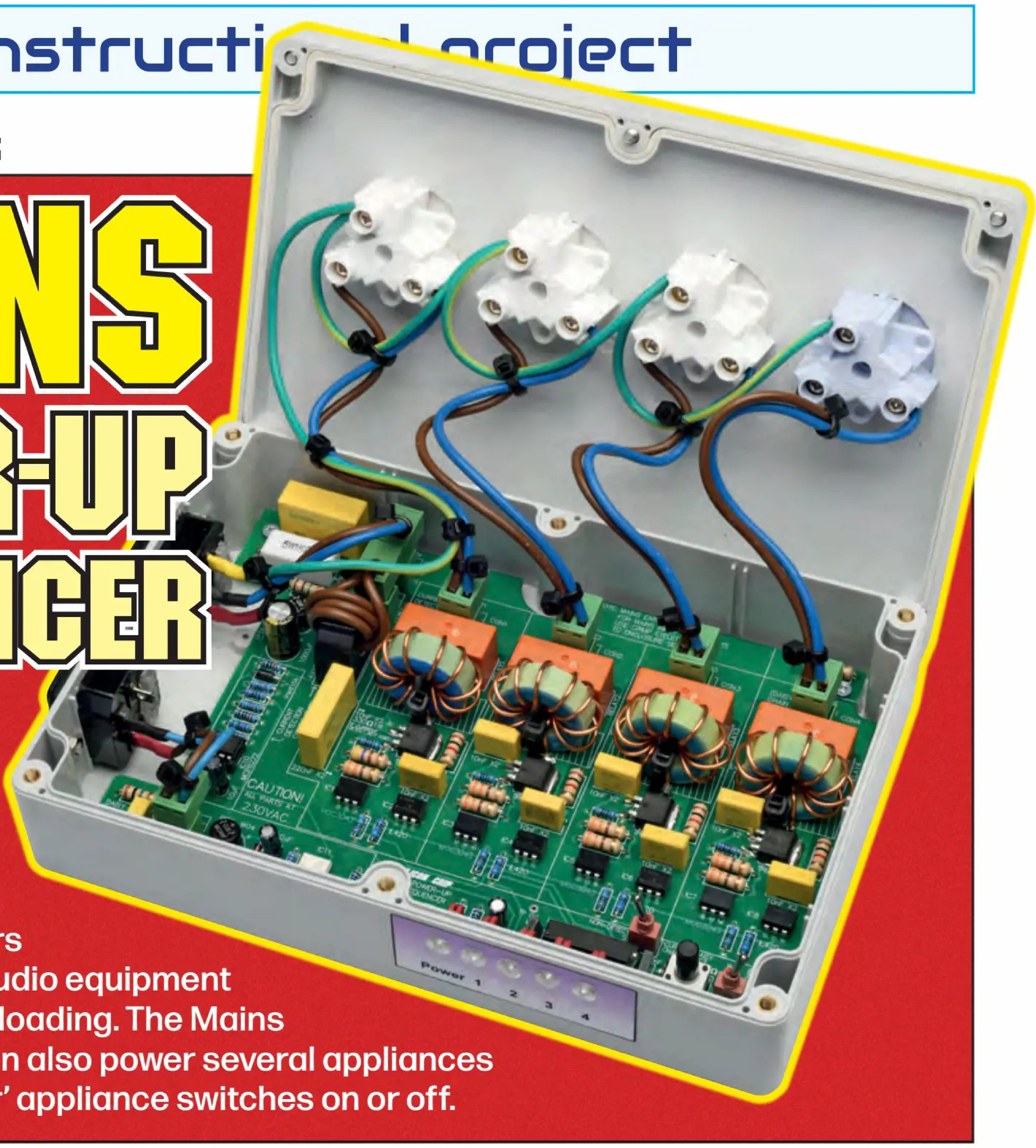
That's all we have room for in this issue. We will pick up where we left off in the third article next month, continuing our chronological list of electronic pioneers. PE

The Edison light bulb enclosed in a cage. *Source:* https://w.wiki/7AsG

A replica of the upstairs level of Edison's Menlo Park lab. *Source:* https://w.wiki/7AsR

PART 1 OF JOHN CLARKE'S

MAINS POWER-UP SEQUENCER



This Mains Power-Up Sequencer solves many problems caused by powering up several devices simultaneously, including circuit breakers tripping, thumps from audio equipment and modem/router overloading. The Mains Power-Up Sequencer can also power several appliances on or off when a 'master' appliance switches on or off.

You might have run into problems switching on several appliances at once, eg, using the switch on a mains outlet. You might have a bank of equipment that all needs to be powered up, but you would prefer to do it in sequence with the convenience of a single switch. Sometimes, if you switch everything on at once, it can trip the mains circuit breaker.

There can also be a sudden drop in mains voltage when switching on a bank of equipment due to the high initial current draw that causes other equipment to reset or act up.

Similarly, the high initial current can trip the circuit breaker when you have several personal computers that are all switched on together, such as in a school or office.

Additionally, powering up several computers at one time can cause them all to try to access the network/internet at the same time, overloading the router and causing slow startups or even lockups. Staggering the powering up of each computer by a few seconds can prevent this.

The Power-Up Sequencer can address these concerns. It includes four mains outlets that can switch on equipment sequentially, with a delay between each. If four outlets are insufficient, then a second Sequencer can be added that daisy chains from the first unit.

Daisy-chained Sequencers can be powered from a separate power circuit to the first Sequencer, allowing for more devices than can be plugged into a single GPO (general purpose mains outlet). The separate power circuit can even be from a different phase.

Not only does the Sequencer power up equipment in an orderly fashion but it can also be used to power down in sequence.

Warning: Mains Voltage

All circuitry within the Mains Sequencer operates at Line (mains) voltages. It would be an electrocution hazard if built incorrectly or used with the lid open. Only build this if you are fully experienced in building mains projects.

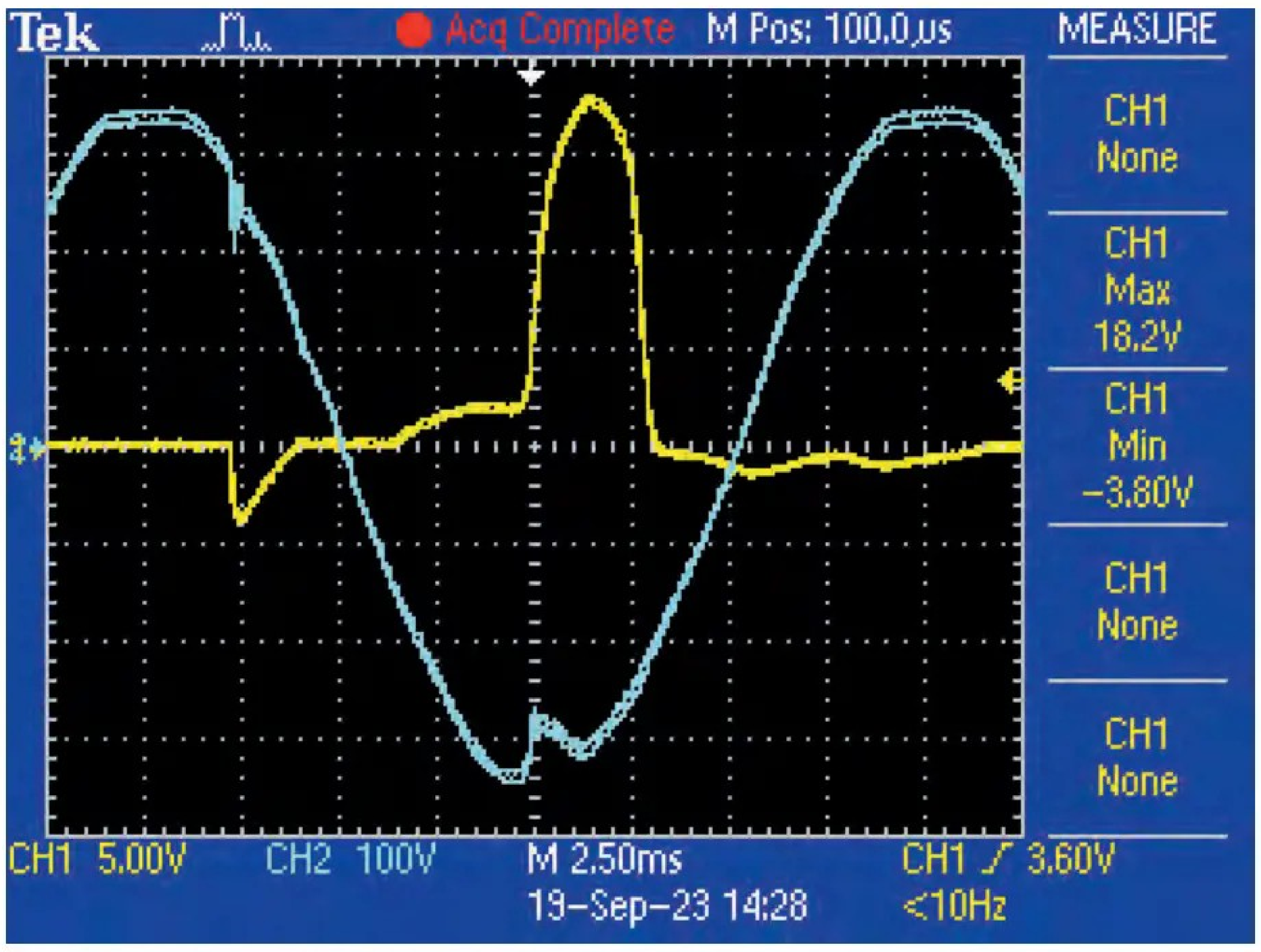
Another feature is the ability to power up and down multiple devices by switching one piece of equipment on and off. That can be useful when equipment is difficult to access and a single, more accessible switch can be used for the on and off powering sequence.

For example, you could have your receiver, amplifier and DVD player automatically switch on when you power up your TV by remote control.

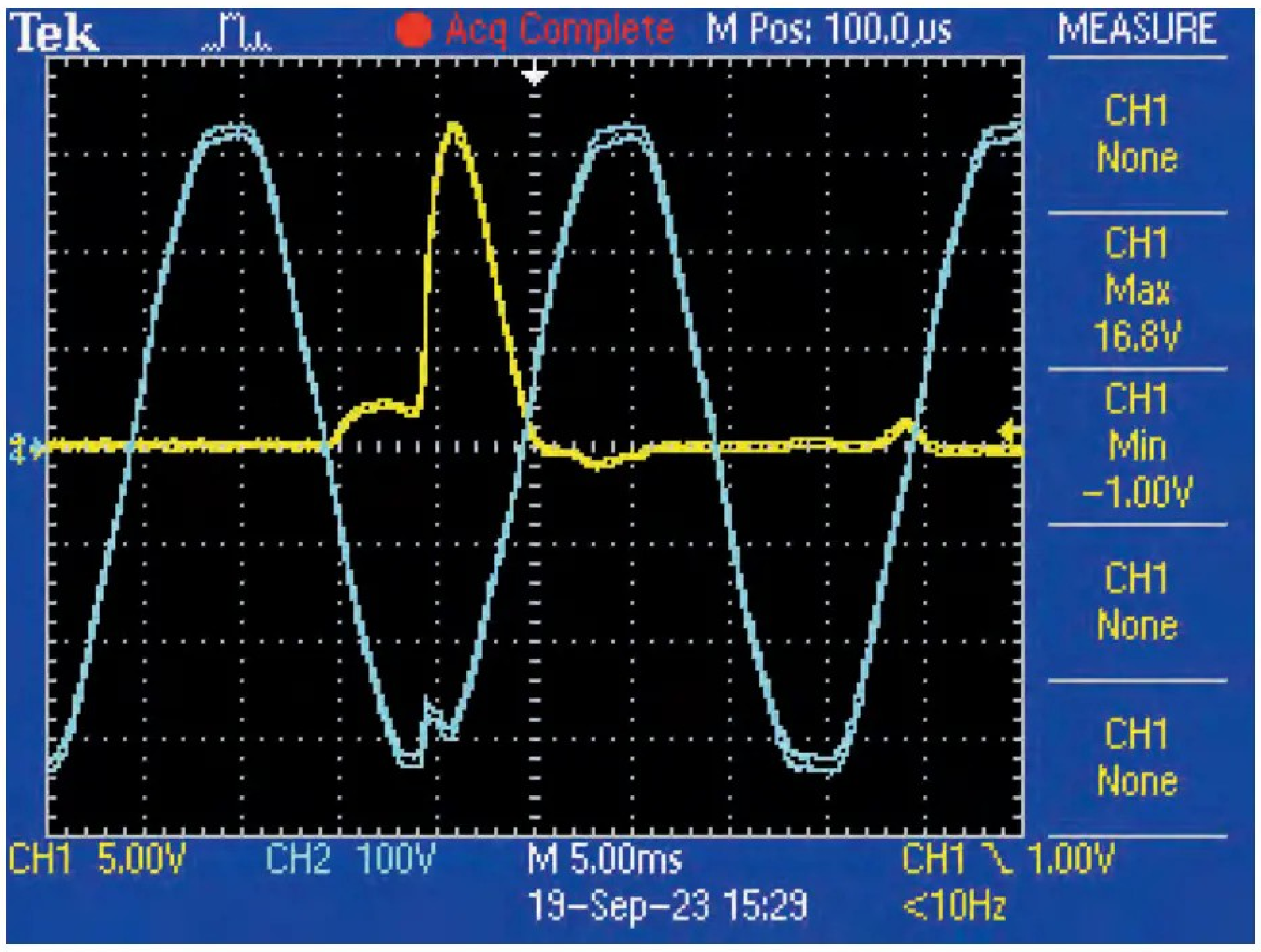
Most equipment draws a substantial current over the first few mains cycles when powering up, often described as inrush current. With some appliances, this current is because a large capacitance needs to be charged. These draw a high initial current before the capacitor voltage rises and the current reduces. In other cases, it can be due to a motor spinning up.

Typically, the inrush current won't cause a circuit breaker to trip if only one appliance is switched on at a time. However, with more devices switched at the same time, the current is multiplied. Switching them on in sequence will avoid that.

Mains Power-up Sequencer pt1



Scope 1: the mains voltage (cyan) and current (yellow) drawn by three amplifiers in parallel that was switched on just after the mains voltage peak. After a small initial current flow, it drops to zero, followed by a big spike to 182A as the amplifiers' capacitor bank starts to charge.



Scope 2: by switching the amplifiers on precisely at the zero crossing, we reduce the inrush current somewhat, to 168A. The reduction will be much greater for devices with a high power factor or power-factor correction (PFC).

It should be noted that the Sequencer is not designed for electric motors such as power tools. If you need to reduce the startup current for motorised appliances, we have published soft starters that are more applicable:

- Active Mains Soft Starter (February & March 2024).
- Soft Starter for Power Tools (July 2013).
- The SoftStarter (April 2013).

Peak currents

As an example of the initial surge current drawn by an appliance, we measured the current initially drawn by a 25V DC power supply that uses a 125VA toroidal transformer to charge two parallel 6800µF capacitors via a bridge rectifier. We measured current using a current transformer calibrated to produce 1V per 10A. The results can be seen in Scope 1.

The cyan (channel 2) trace shows the mains voltage, while the yellow trace (channel 1) shows the current. Note that we show the current 180° out of phase with the voltage so that the two waveforms can be seen more easily, without one obscuring the other.

Upon powering the 25V supply, it drew a maximum of 38A on the first half cycle, and 182A on the second half cycle.

The first half cycle current is lower because the power was switched on later in the mains half cycle, but the next half cycle had the full waveform, so the current was higher. When power is applied closer to the peak of the mains voltage, there will be a steep rise in the current drawn.

If more than one of these supplies were powered up simultaneously, the current drawn from the GPO would add up. It is no wonder that a circuit breaker can trip if several appliances are switched on at the same time.

For our Power-Up Sequencer, as well as staggering when power is applied to each appliance, we switch them on when the mains voltage is near the zero voltage crossing point. That allows the current to rise more slowly since the applied voltage follows the mains sinewave, instead of a peak voltage of up to about 325V applied instantaneously if power were applied at any time during the mains cycle.

This is shown in Scope 2. The current rises from the start of the waveform just past the zero crossing as the mains voltage rises and results in a 168A peak. That's still high because this appliance only really draws current near the peak of the voltage waveform. However, other appliances with a better power factor (PF) will benefit more from this zero-crossing switching.

Sequencer options

There are two options. The first is the master/slave feature, which involves monitoring the current drawn from the OUT1 GPO socket. The second is the Mains Detect Input, which can be used for daisy chaining.

Switching on each GPO in sequence is done at an adjustable rate. The power-on and power-off sequence intervals are independent and can each be adjusted between 100ms and 23s.

Mains Power-Up Sequencer Features

- Four independently-controlled 10A mains outputs (up to 10A total draw)
- Output switch on at mains zero crossing
- Adjustable power on & off sequence rates
- First on, first off (forward) or first on, last off (reverse) power-down sequence option
- Daisy-chaining for more outputs and extra current
- Master channel Current Detection option
- Separate Mains Input Detection option
- Number of outlets selection option (1-4)
- Relay switching for high efficiency with inrush/switch-off current spike protection
- Sequence indicators
- Multiple startup options
- Uses standard IEC mains cables and GPO outlets
- Housed in a rugged enclosure

The order that the outputs are sequentially switched on is OUT1, OUT2, OUT3 and then OUT4. When switching off, you can select the reverse sequence order of OUT4, OUT3, OUT2 and then OUT1, or the forward sequence of OUT1, OUT2, OUT3 and then OUT4.

We have provided several options so that the Sequencer can be as versatile as possible. That includes the option to build the unit with between one and four outlets, since some applications may not require four mains outlets. When the Sequencer is set up for fewer outlets, the powering sequences will be truncated to operate only over the installed number of outlets.

Presentation & configurations

The Sequencer comprises a rugged plastic enclosure with an IEC mains socket on the left side of the enclosure and four GPO mains sockets on the lid. The IEC mains socket provides input power using a standard IEC mains lead. A second IEC mains socket can be installed for Mains Input Detection, such as when daisy-chaining two Sequencers together.

Fig.1 shows what the various inputs and outputs do. The basic configuration for building the Sequencer is without the second (lower) input, in which case, the outputs switch on in sequence when power is applied, and they all switch off at once when power is lost.

It can also be built without the second input but with Current Detection for OUT1. In that case, OUT1 is the master socket and OUT2, OUT3 & OUT4 are the slaves. The slave outputs switch on in sequence when it detects the master device drawing current from OUT1. They switch off in sequence when the appliance stops drawing power from OUT1.

The third configuration is with the Mains Detect Input but without Current Detection. Nothing happens when power is first applied to the unit in this case. It waits until it detects a mains voltage at the Mains Detect Input, then switches on the four outputs in sequence.

If voltage is no longer detected at the Mains Detect Input, the four outputs switch off sequentially. They all switch off immediately if the main power input is lost. Note that no power is drawn from the supply fed to the Mains Detect Input.

While the Mains Detect Input is primarily intended for daisy-chaining, it can also trigger switching the four outlets on in sequence when another device is switched on via a GPO switch or other mains-interrupting device.

The first and most basic configuration is without the Mains Input Detect circuitry or Current Detection circuitry and is easier to build. The disadvantages are that you have to switch it on at the wall, and all the outlets switch off immediately when it is switched off, rather than in sequence. Whether or not that is a problem depends on your situation.

An example of where devices may need to be switched off in sequence is where you have an audio processor or mixer ahead of one or more power amplifiers. If the mixer or audio processor is switched on after the amplifiers or off before the amplifiers, a loud noise can be produced in the loudspeakers driven by the amplifiers.

That is because the mixer or audio processor can produce a large voltage swing in the audio signal at switch-on or switch-off. So ideally, the amplifiers need to be switched on after the audio processor and off before the audio processor. Therefore, one of the options would be required.

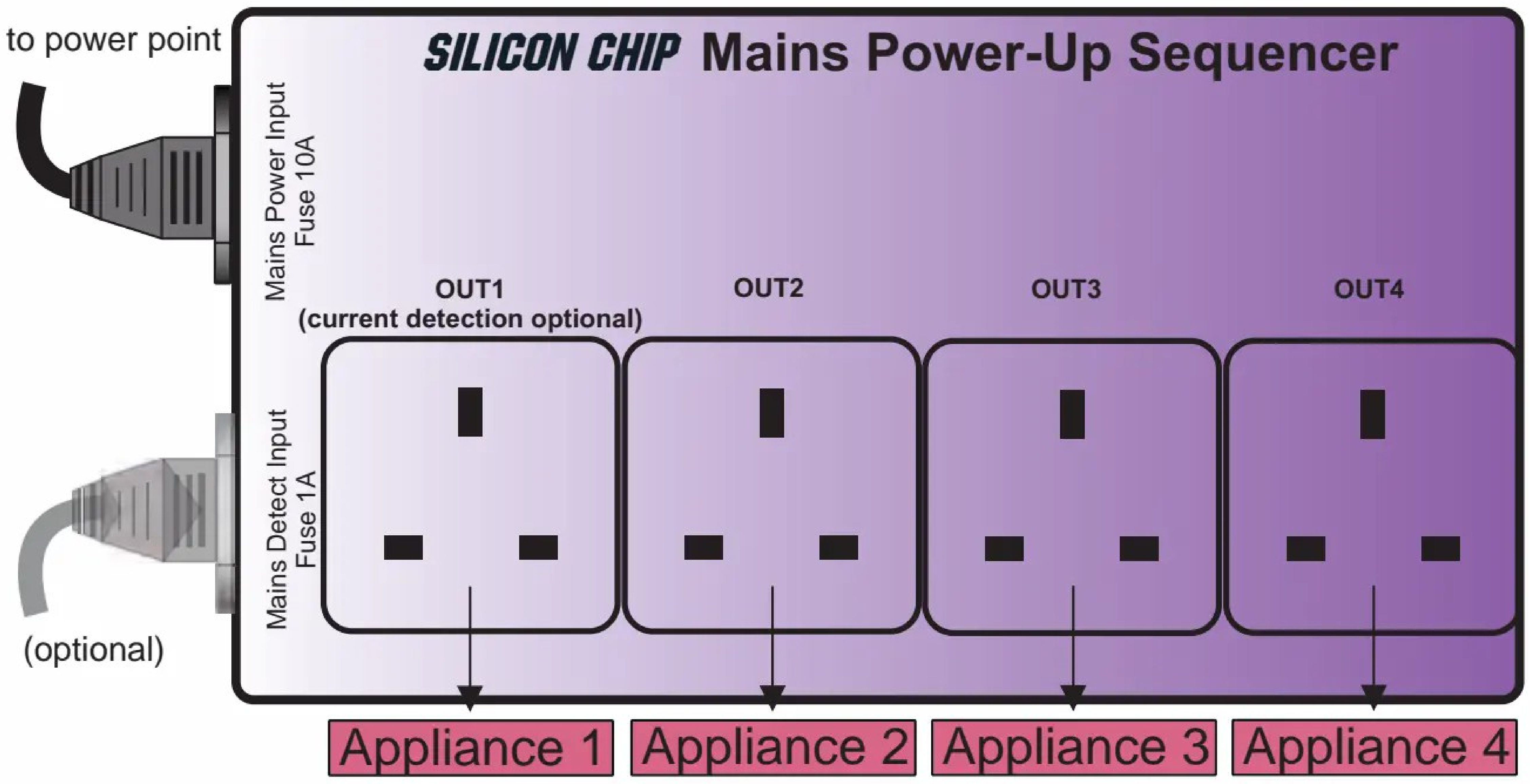


Fig.1: the Mains Power-up Sequencer can have three primary configurations. It can be built with or without the optional Mains Detect Input that allows it to be triggered from a separate, isolated mains input (useful for daisy-chaining). It can also be built with current detection for OUT1 that will trigger the switching of OUT2-OUT4 but, in that case, the Mains Detect Input cannot be used.

Both of the other configurations, with either the Mains Input Detect circuitry or Current Detection circuitry (but not both), offer power-on and power-off sequencing.

Fig.2 shows how you can add more sequencer outputs by daisy chaining two (or more) Sequencer units. The primary Sequencer can have any of the three possible configurations. The other Sequencers need to be configured with the Mains Detect Input option.

OUT4 from the primary Sequencer applies voltage to the Mains Detect Input of the second Sequencer using a piggyback mains plug lead (or double adaptor). In this way, when OUT4 of the primary Sequencer is powered, it triggers the second Sequencer to start providing power to its outputs and so on. The piggyback plug allows an appliance also to be powered from OUT4 so you don’t lose an output.

A delay can be included in the second unit so that its OUT1 outlet does not switch on as soon as the OUT4 on the primary unit is powered.

Note that if the primary and daisy-chained Sequencers are set for a forward off-sequence (OUT1, OUT2, OUT3 then OUT4), the daisy-chained off-sequence will begin after the primary sequence has finished. However, if the off-sequence is in reverse (OUT4, OUT3, OUT2 then OUT1), the daisy-chained off cycle will start as soon as the primary Sequencer begins its off-sequence.

Besides using the forwards off-sequence, there are ways to deal with this. One is to set a greater delay for the daisy-chained off-sequence so that it starts after the primary sequence has finished, despite being triggered earlier. Also, if the primary Sequencer

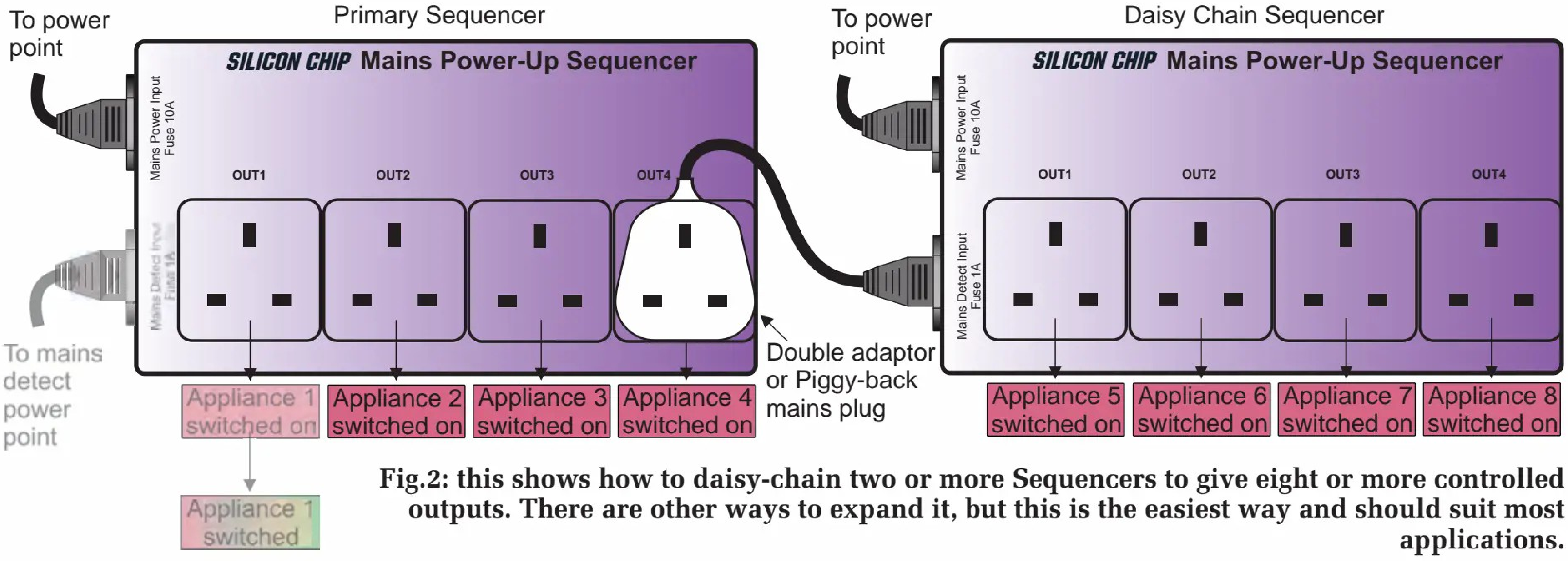

To power point
Primary Sequencer
SILICON CHIP Mains Power-Up Sequencer
Mains Power Input Fuse 10A
Mains Detect Input Fuse 1A
OUT1
OUT2
OUT3
OUT4
To mains detect power point
Appliance 1 switched on
Appliance 2 switched on
Appliance 3 switched on
Appliance 4 switched on
Appliance 1 switched
Double adaptor or Piggy-back mains plug
To power point
Daisy Chain Sequencer
SILICON CHIP Mains Power-Up Sequencer
Mains Power Input Fuse 10A
Mains Detect Input Fuse 1A
OUT1
OUT2
OUT3
OUT4
Appliance 5 switched on
Appliance 6 switched on
Appliance 7 switched on
Appliance 8 switched on

Fig.2: this shows how to daisy-chain two or more Sequencers to give eight or more controlled outputs. There are other ways to expand it, but this is the easiest way and should suit most applications.

off-rate is twice the daisy-chained Sequencer off rate, the outputs from each will switch off alternately between the two.

There's also the possibility of connecting the Mains Detect Inputs of secondary Sequencers to each of the OUT1-OUT4 outputs of a primary Sequencer if you need them to switch on and off in a neat sequence, with primary delays set to be longer than the secondaries.

Circuit details

Fig.3 shows the full circuit for the Power-Up Sequencer. It is based around microcontroller IC9, which monitors the Mains Detect Input or the current flow through an appliance plugged into OUT1. It also drives the circuitry that powers the four GPOs that supply power to the appliances. Other connections to the microcontroller are for setting the on and off sequence delays and other options.

Switching mains to each GPO at OUT1-OUT4 is achieved using a relay and a Triac in parallel for each outlet. The Triacs are 600V bidirectional switches capable of conducting 30A continuously and up to 270A over one 20ms mains cycle. The Triac is included to protect the relay contacts from damage and a short life due to high initial surge currents drawn by appliances at power-up.

So, instead of using the relay contacts directly, we first switch on the Triac and then the relay some 300ms later. This means that the initial startup current by an appliance is connected via the Triac, with the relay contact closing afterwards, once the current has dropped.

In the same way, the Triac is used to hold power on when the relay is switched off for 100ms, giving time for the relay contacts to fully open before the Triac switches off. That protects the relay contacts from voltage transients that may damage the relay contacts over time.

The Triac is protected from voltage transients by a snubber circuit across it that comprises a 10nF X2 rated capacitor and 330Ω 1W resistor in series for the OUT2, OUT3 and OUT4 circuits.

These values are labelled as R1 and C1 for OUT1 because they depend on whether this mains channel is used to detect whether an appliance is switched on or off for Current Detection. If Current Detection is being used, a 220nF X2-rated capacitor and series 470Ω 1W resistor are used instead of the values mentioned above.

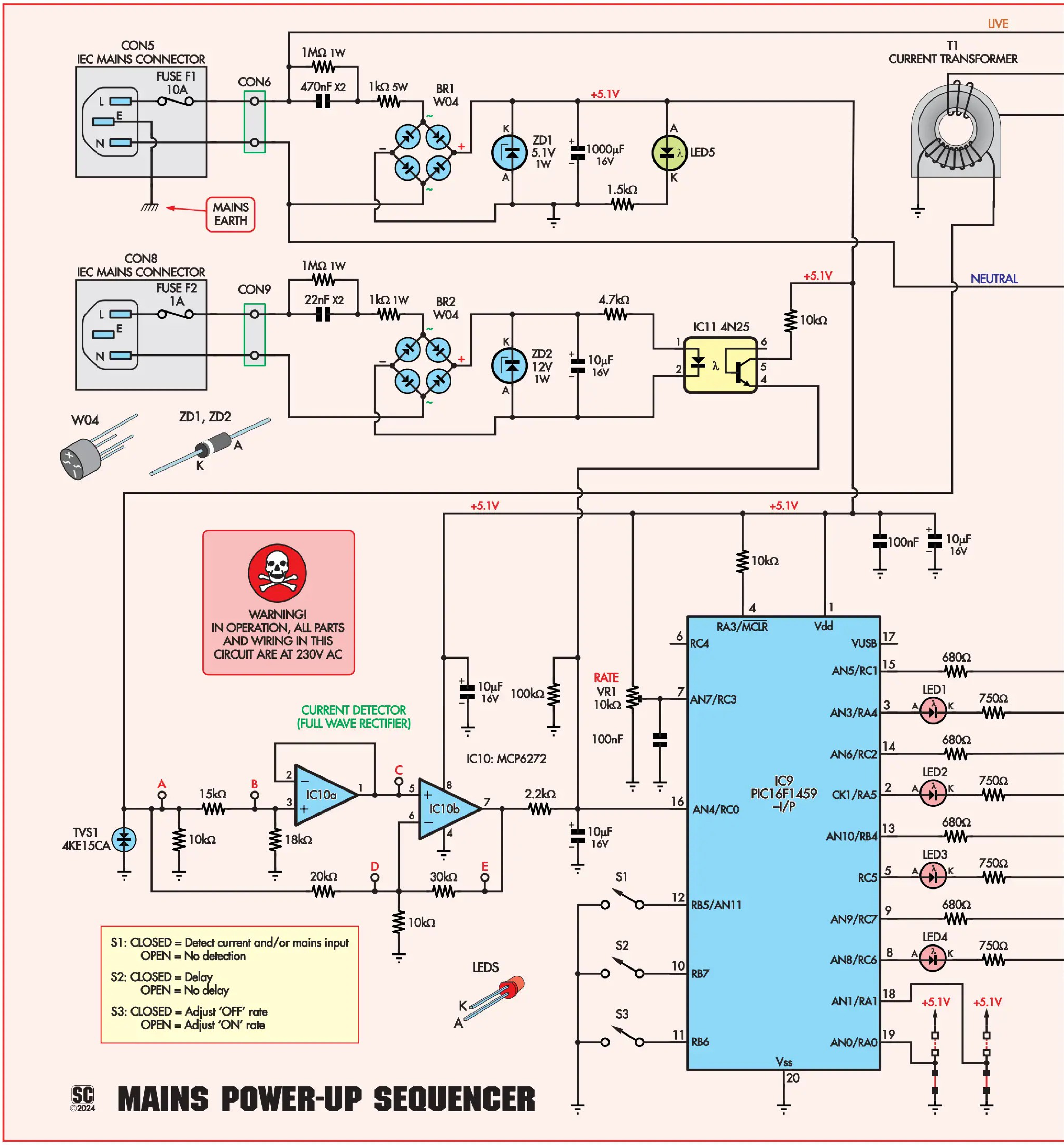
The relay and the Triac for each output are driven using separate optically-coupled Triac driver ICs. These incorporate lower current rated Triacs that are switched on via LEDs within the ICs.

The optically-coupled Triac drivers (IC1 and IC2 for OUT1) are similar. However, IC1 will only trigger the internal Triac near the zero-voltage crossing of the mains waveform, when the instantaneous voltage is under 25V.

So IC1 will only trigger TRIAC1 at the start of the mains waveform, and any surge current drawn by the appliance will be very low to begin with (since the voltage is low)

SILICON CHIP Mains Power-Up Sequencer
Mains Power Input Fuse 10A
Mains Detect Input Fuse 1A
OUT1
OUT2
OUT3
OUT4
Power
1
2
3
4

While the prototype uses Australian mains outlets, they can be replaced with UK types or extension cords.


LIVE
T1
CURRENT TRANSFORMER
CON5
IEC MAINS CONNECTOR
FUSE F1
10A
L
E
N
CON6
1MΩ 1W
470nF X2
1kΩ 5W
BR1
W04
+5.1V
K
ZD1
5.1V
1W
A
1000µF
16V
A
LED5
K
1.5kΩ
MAINS
EARTH
CON8
IEC MAINS CONNECTOR
FUSE F2
1A
CON9
1MΩ 1W
22nF X2
1kΩ 1W
BR2
W04
4.7kΩ
+5.1V
10kΩ
ZD2
12V
1W
10µF
16V
IC11 4N25
NEUTRAL
W04
ZD1, ZD2
A
K
+5.1V
+5.1V
100nF
10µF
16V
10kΩ
WARNING!
IN OPERATION, ALL PARTS
AND WIRING IN THIS
CIRCUIT ARE AT 230V AC
10µF
16V
100kΩ
RATE
VR1
10kΩ
100nF
CURRENT DETECTOR
(FULL WAVE RECTIFIER)
IC10: MCP6272
A
15kΩ
B
IC10a
C
IC10b
2.2kΩ
TVS1
4KE15CA
10kΩ
18kΩ
20kΩ
D
30kΩ
E
10kΩ
10µF
16V
S1
S2
S3
LEDS
K
A
S1: CLOSED = Detect current and/or mains input
OPEN = No detection
S2: CLOSED = Delay
OPEN = No delay
S3: CLOSED = Adjust 'OFF' rate
OPEN = Adjust 'ON' rate
RA3/MCLR
Vdd
RC4
VUSB
AN5/RC1
AN7/RC3
AN3/RA4
AN6/RC2
IC9
PIC16F1459
–I/P
CK1/RA5
AN4/RC0
AN10/RB4
RC5
RB5/AN11
AN9/RC7
AN8/RC6
RB7
AN1/RA1
RB6
AN0/RA0
Vss
680Ω
LED1
750Ω
680Ω
LED2
750Ω
680Ω
LED3
750Ω
680Ω
LED4
750Ω
+5.1V
+5.1V
SC ©2024
MAINS POWER-UP SEQUENCER

and only rise as the mains voltage increases over time. The inductor (eg, L1) in series with the Triac reduces the maximum current rise rate to a safe level.

Driving the relay

For the OUT1 mains channel, IC2 drives the relay coil directly. The snubber across the coil comprising a 10nF X2 rated capacitor and 1kΩ 1W resistor limits voltage spikes when the IC switches off and current flow through the relay coil ceases. This snubber also prevents the relay from buzzing when powered off due to current leakage through IC2's internal Triac.

In a typical circuit, the snubber would be across the Triac pins, but for our purposes, this would provide current through the relay coil when the Triac is off, so the relay will tend to vibrate (buzz). This leakage current is insufficient to switch the relay, but it can still cause it to vibrate. By placing the snubber across the relay coil,

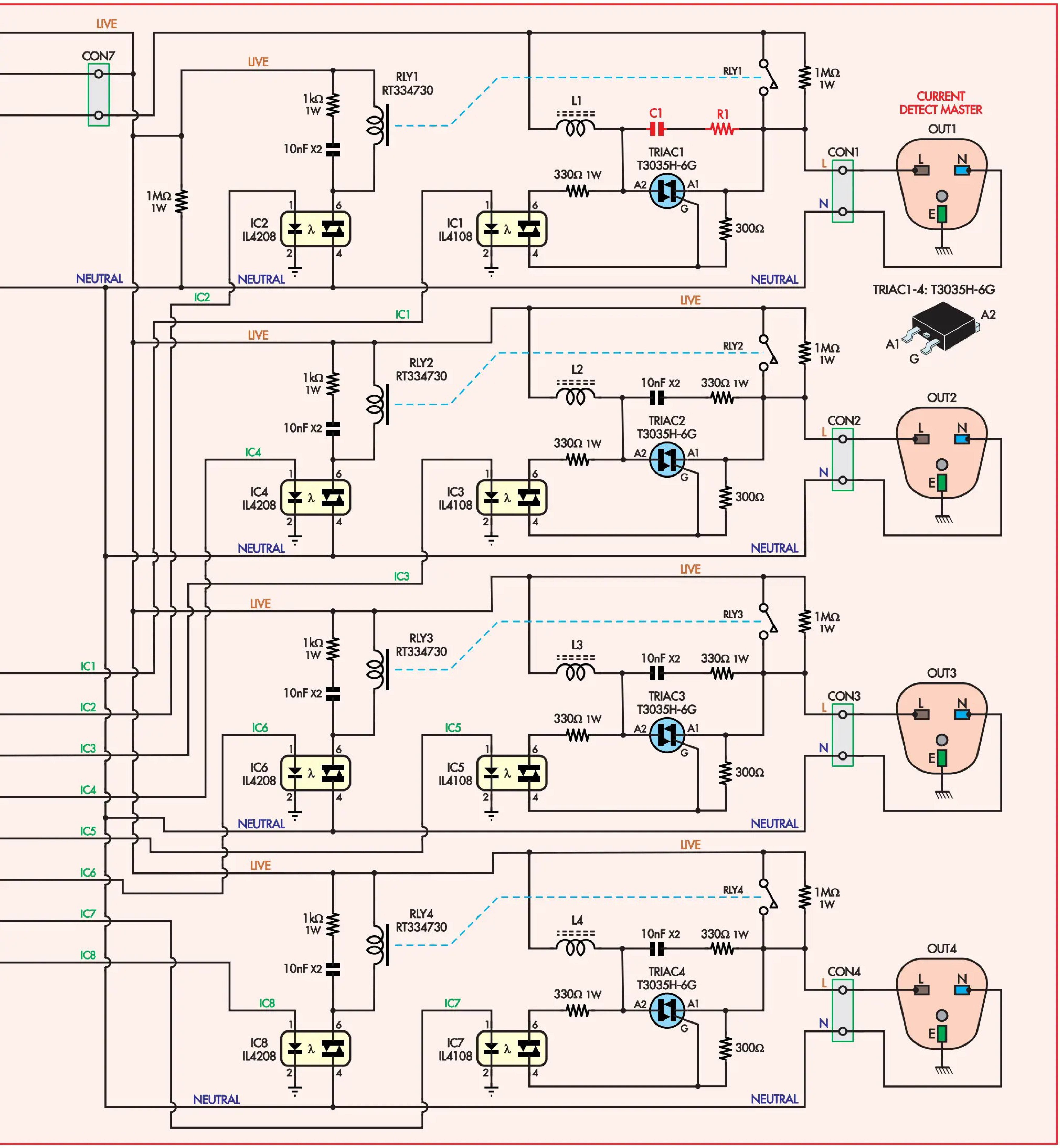

LIVE
CON7
LIVE
RLY1
RT334730
1kΩ
1W
10nF X2
1MΩ
1W
IC2
IL4208
NEUTRAL
NEUTRAL
IC2
IC1
IC1
IL4108
L1
C1
R1
RLY1
1MΩ
1W
TRIAC1
T3035H-6G
A2
A1
G
330Ω 1W
300Ω
NEUTRAL
CURRENT
DETECT MASTER
OUT1
CON1
L
N
L
N
E
TRIAC1-4: T3035H-6G
A2
A1
G
LIVE
RLY2
RT334730
L2
10nF X2
330Ω 1W
TRIAC2
T3035H-6G
IC4
IL4208
IC3
IL4108
OUT2
CON2
IC3
LIVE
RLY3
RT334730
L3
TRIAC3
T3035H-6G
IC6
IL4208
IC5
IL4108
OUT3
CON3
IC1
IC2
IC3
IC4
IC5
IC6
IC7
IC8
LIVE
RLY4
RT334730
L4
TRIAC4
T3035H-6G
IC8
IL4208
IC7
IL4108
OUT4
CON4
NEUTRAL

Fig.3: the complete Sequencer circuit. It consists of five main blocks: output switching (the entire right-hand page), power supply (upper-left corner), optional Mains Detect Input (below the power supply), Current Detection (lower left plus T1 at top middle) and control (IC9 and surrounding components).

this current bypasses the coil.

Both types of Triac drivers have special voltage-clamping features that prevent them from conducting (switching on) when mains power is suddenly applied to the circuit. That can happen even with the internal opto-coupled LED off. The clamping feature allows a voltage rise of up to 10kV per microsecond (10kV/μs) to occur without the internal Triac self-triggering.

The LED drive current for the Triac drivers is low compared to many other similar devices, with a lower limit of just 2mA (or 5mA for entirely inductive loads) for the IL4108 (or IL410) and 2mA for the IL4208 or IL420.

That means we can get away with a simpler power supply for this part of the circuit that only has to deliver a modest current, even when all mains outputs (OUT1, OUT2, OUT3 and OUT4) are switched on.

The IL4108 or IL410 IC used for switching the Triac is only switched on momentarily before the relay driver is switched on using the IL4208 or IL420. This means that when all outlets are on, the total drive for the opto-coupled Triac drivers will be around 8mA. We actually drive each at a little more than the required 2mA to allow for a safety margin.

The Triac and relay driving circuitry is the same for all four channels. The only difference is the aforementioned snubber component value variation for OUT1 if current sensing is used.

Microcontroller functions

Digital outputs RC1 (pin 15) and RA4 (pin 3) of microcontroller IC9 drive the opto-couplers to control OUT1, while other similar digital outputs control the other three channels. A 680Ω resistor limits the current to IC1's LED to a little over 5mA. For IC2, there is an indicator LED (LED1) in series with the LED within IC2, so we use a 750Ω resistor in series to ensure the current is at least 2mA.

Switches S1 to S3 connect to the RB5, RB7 and RB6 digital inputs (pins 12, 10 & 11) of IC9, respectively, and these inputs have internal pullups. So each input is sensed as a high level when the switch is open and as a low when the switch is closed, pulling the input to the 0V rail.

Switch S1 selects whether the sequencer detects appliance current or uses mains detection. When S1 is open, no current or mains detection is used, so the sequencer starts up whenever mains power is applied.

Switch S2 selects whether the sequencer switches power to the first output immediately or after a delay when triggered. When S2 is closed, there is a delay before switching on or off, equal to the on/off sequence delay. When S2 is open, there is no such delay.

Switch S3 selects whether VR1 adjusts the on-sequence or off-sequence rates. It can also determine whether the off-sequence runs in a forward direction or reverse.

VR1 is connected across the 5.1V supply, so the wiper provides a varying

Parts List – Mains Power-Up Sequencer

1 double-sided PCB coded 10108231, 203 × 134mm
1 Gainta G317-IP67 or G218 222 × 146 × 55mm ABS or polycarbonate IP65/IP67 sealed enclosure [TME G317, TME G218]
1 set of panel labels (top and side panel)
1 IEC C14 panel-mount mains input connector with integral fuse (CON5)
1 10A mains IEC lead
1 10A M205 fast blow fuse (F1)
5[1] vertical-mounting 15A 300V two-way pluggable terminal blocks, 5.08mm pitch (CON1-4, CON6)
4[1] 13A chassis-mount mains sockets (OUT1-OUT4) [eg, RS 500-0459] ●
4[1] 28 × 14 × 11mm compressed powdered iron toroidal cores (L1-L4)
4[1] Schrack RT33473 16A NO 230VAC coil relays (RLY1-RLY4) **[Farnell 2748015]**
3 SPDT subminiature toggle switches (S1-S3)
1 9mm PCB-mount vertical 10kΩ linear potentiometer (VR1)
1 20-pin DIL IC socket
5[1] 16kV isolation Fresnel 5mm LED bezels (Cliplite CLB300CTP) **[Farnell 2748731]**

Wire/cable/hardware

4[1] 50cm lengths of 1.25mm diameter enamelled copper wire (for L1-L4)
1 820mm length of blue 10A mains-rated wire
1 900mm length of brown 10A mains-rated wire
1 500mm length of green/yellow striped 10A mains-rated wire
1 75mm length of 10mm diameter heatshrink tubing
1 60mm length of 5mm diameter heatshrink tubing
1 250mm length of 1mm diameter heatshrink tubing (for LED leads)
2 M3 × 10mm Nylon countersunk head machine screws (for CON5)
4 M3 × 6mm panhead machine screws (for attaching the PCB to the enclosure)
2 M3 hex nuts
4[1] 200mm cable ties (for L1-L4)
15 100mm cable ties

Semiconductors

4[1] IL410 or IL4108 zero-switching Triac output opto-couplers, DIP-6 (IC1, IC3, IC5 & IC7) **[Farnell 1045434, 1612489]**
4[1] IL420 or IL4208 random-switching Triac output opto-couplers, DIP-6 (IC2, IC4, IC6 & IC8) **[Farnell 1469488]**
1 PIC16F1459-I/P microcontroller programmed with 1010823A.hex, DIP-20 (IC9)
4[1] T3035H-6G 30A Triacs (TRIAC1-TRIAC4), D2PAK **[Farnell 2778110]**
1 400V 1A W04 bridge rectifier (BR1)
1 5.1V 1W zener diode (ZD1)
5[1] 5mm high-brightness LEDs (eg, one green and four red) (LED1-LED5)

Capacitors

1 1000µF 16V PC electrolytic
1 10µF 16V PC electrolytic
1 470nF X2-rated mains capacitor
1 220nF X2-rated mains capacitor **(10nF if current detect feature is not used)**
2 100nF MKT polyester
7[1] 10nF X2-rated mains capacitors

Resistors *(all ¼W 1% unless otherwise specified)*

6[1] 1MΩ 1W 5%
1 100kΩ
1 10kΩ
1 1.5kΩ
1 1kΩ 5W 5%

4[1] 1kΩ 1W 5%
4[1] 750Ω
4[1] 680Ω
7[2] 330Ω 1W 5% **(8 if current detection is not used)**
4[1] 300Ω

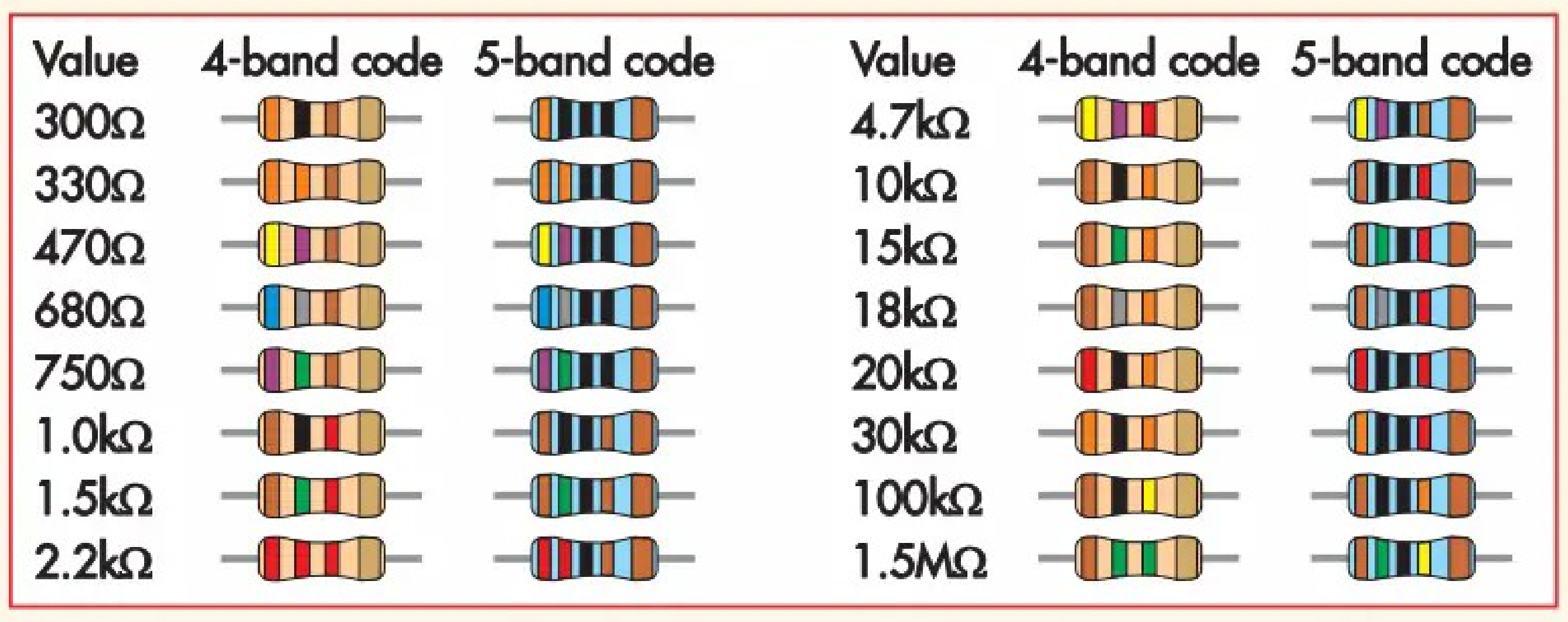
Alternative parts instead of GPO sockets (●)
4 cordgrip grommets
4 2m mains extension cords (or 4 mains line sockets and 8m of 10A mains cable)
5 crimp eyelets suitable for 4-6mm² wire
1 M4 × 20mm panhead machine screw
1 M4 hex nut
1 M4 star washer

Note: UK mains outlets are larger than the Australian types shown in the photos. We recommend the alternative approach using cut-off extension cords. If you decide to use four sockets, you will need to stagger them vertically to leave enough plastic between the cut-outs for the lid to retain its integrity. We'll have more details on that next month.

Extra parts for Current Detection feature

1 vertical-mounting 15A 300V two-way pluggable terminal block, 5.08mm pitch (CON7)
1 AC1010 10A current transformer (T1)
1 MCP6272-E/P dual rail-to-rail op amp, DIP-8 (IC10)
1 8-pin DIL IC socket
1 (P)4KE15CA transient voltage suppressor (TVS1)
2 10µF 16V PC electrolytic capacitors
1 200mm length of 10A brown mains-rated wire
1 200mm cable tie

Resistors *(all ¼W 1%)*
1 30kΩ
1 20kΩ
1 18kΩ
1 15kΩ
2 10kΩ
1 2.2kΩ
1 470Ω 1W 5%


Value
4-band code
5-band code
300Ω
330Ω
470Ω
680Ω
750Ω
1.0kΩ
1.5kΩ
2.2kΩ
Value
4-band code
5-band code
4.7kΩ
10kΩ
15kΩ
18kΩ
20kΩ
30kΩ
100kΩ
1.5MΩ

Extra parts for Mains Input Detection feature

1 IEC panel-mount mains input connector with integral fuse (CON8)
1 mains IEC lead
1 1A M205 fast blow fuse (F2)
1 vertical-mounting 15A 300V two-way pluggable terminal block, 5.08mm pitch (CON9)
2 M3 × 10mm Nylon countersunk head machine screws (for CON8)
2 M3 hex nuts
1 75mm length of brown 7.5A mains-rated wire
1 75mm length of blue 7.5A mains-rated wire
1 40mm of 0.5mm diameter heatshrink tubing
1 4N25 phototransistor opto-coupler, DIP-6 (IC11)
1 400V 1A W04 bridge rectifier (BR2)
1 12V 1W zener diode (ZD2)
1 10µF 16V PC electrolytic capacitor
1 22nF X2-rated mains capacitor
1 1MΩ 1W 5% resistor
1 10kΩ ¼W 1% resistor
1 4.7kΩ ¼W 1% resistor
1 1kΩ 1W 5% resistor

Increasing the current rating to 13A

The 10A maximum rating is mainly due to the mains input socket with integral M205 fuse. As UK mains leads include a fuse, you could upgrade this device to a 13A rating by using a 15A unfused input socket (eg, Farnell 1176790), 13A input lead and 13A mains-rated wire instead of 10A throughout.

[1] reduce quantities by one for each output not fitted
[2] reduce quantity by two for each output not fitted

voltage to the AN7 analog input of IC9 (pin 7). This voltage is bypassed by a 100nF capacitor to present a low impedance when IC9 reads the voltage using its internal analog-to-digital converter. Any parameters set using VR1 are stored in flash memory within IC9, so they remain even if power is switched off.

Reduced output channels

Initially, all four outputs are active. However, if you don't need all four, you can leave them off and tell the microcontroller not to use those outputs.

The RA0 and RA1 digital inputs (pins 19 & 18) are initially tied to ground on the PCB. The small tracks connecting RA0 and RA1 to 0V can be broken and connected to the nearby track on the PCB's top side, which joins to the +5.1V supply. A table next month will show which connections are required for any number of outputs. That changes how the output sequence operates in software.

Unused output channels do not need to have their components populated on the PCB.

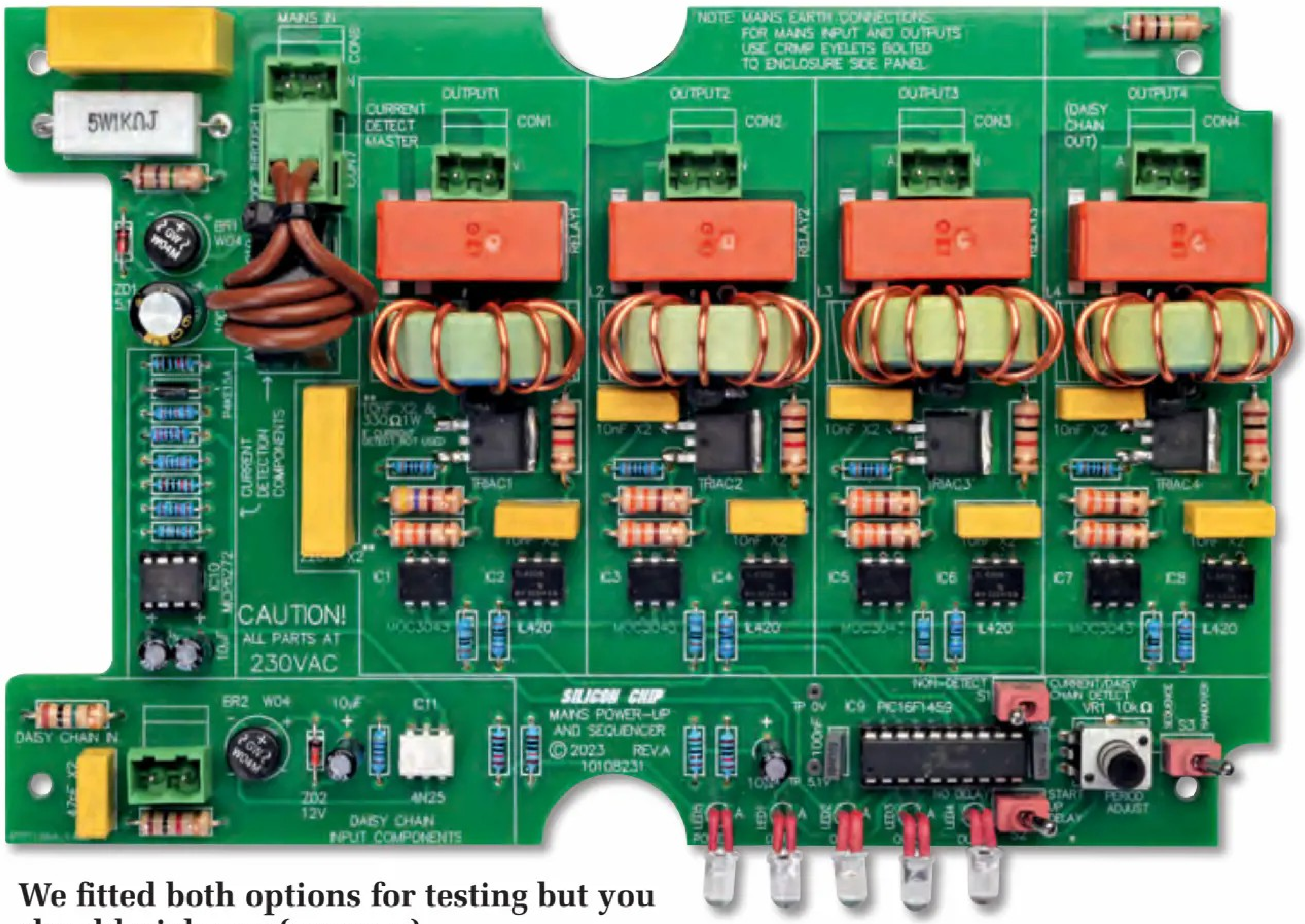
Mains detection

The separate mains presence detection is via input IEC connector CON8. A series 22nF X2 capacitor is used to apply and limit current to bridge rectifier BR2, while 12V zener diode ZD2 limits the voltage across the output of the bridge. The resulting DC supply is filtered with a 10µF capacitor.

The 22nF capacitor provides an impedance of 144.7kΩ at 50Hz (1 ÷ [22nF × 2π × 50Hz]). Therefore, the current that can be drawn is 230V AC ÷ 144.7kΩ = 1.59mA. The 1kΩ 1W resistor in series with the 22nF capacitor limits the surge current through the capacitor when power is first applied, while the 1MΩ 1W resistor across the capacitor discharges it when power is off.

When power is on, the DC supply drives the LED within optically-coupled transistor IC11 via a 4.7kΩ resistor. ZD2 will not normally clamp the voltage to 12V since the current drive to the LED within IC11 means that the rectified voltage is about 8.5V, ie, 1.59mA × 4.7kΩ plus IC11's LED voltage of about 1V.

The zener diode is included just for protection should there be an open-circuit condition. Without it, the 10µF capacitor could be charged to nearly the peak mains voltage (325V) with


CAUTION! ALL PARTS AT 230VAC
SILICON CHIP MAINS POWER-UP AND SEQUENCER

We fitted both options for testing but you should pick one (or none).

catastrophic results, such as the 10µF 16V capacitor exploding.

Current Detection

Current transformer T1 is used for the Current Detection feature of OUT1. It produces a current from its secondary winding that's proportional to the current flow through the Live mains wire. The 10kΩ loading resistor gives about 4V AC output with a current flow of 1A and one turn of the Live mains wire through the current transformer core.

We use four turns through the core, giving about 4V AC with 250mA of current through the primary.

The transformer's primary winding is terminated at the CON7 screw terminal socket. If Current Detection is not used, the two CON7 terminals still need to be joined so that the mains Live connects to OUT1.

Current flowing through an appliance connected to the OUT1 GPO outlet also goes through T1's primary winding, inductor L1 and the snubber comprising a 220nF X2-rated capacitor and series 470Ω 1W resistor. The impedance provided by the 220nF capacitor at 50Hz is around 14.5kΩ, allowing about 15.9mA to flow through the switched-on appliance when OUT1 is off.

Once current is detected, the sequencer will switch full mains power to the appliance.

While T1's transimpedance is not very linear using a 10kΩ loading resistance, we use that relatively high value to improve sensitivity. A 100Ω loading resistor would provide a more linear relationship for accurately measuring current, but only gives a 1V output for a 10A primary current with a single turn through the transformer. We just need to sense when current flows.

Voltage rectification

The output voltage of T1 is positive and negative on each mains half-cycle, but we want a positive voltage to feed to the microcontroller, so we need to rectify it. But it's a small voltage, so we must use precision rectification to avoid any diode voltage losses.

A precision full-wave rectifier is used, made from dual op amp IC10 and associated resistors. The rectification is done purely by the op amps, without added diodes. The gain of this precision rectifier is 1.5 times. Transient voltage suppressor TVS1 clamps the output from T1 to about 13.8V AC. That limits the current into the following op amp inputs to a safe level.

While it may seem impossible to rectify the incoming AC voltage without diodes, it is possible, provided that the op amp has specific characteristics. These include operating correctly (without output phase reversal) with input voltages below its negative supply rail. In addition, the op amp must be able to pull its output close to the negative rail (ground, in this case).

To put it another way, diode junctions within the op amps perform this function without us needing to add external diodes.

We use an MCP6272 dual op amp (IC10) for this full-wave rectification. One stage (IC10a) is connected as a unity gain buffer, while the other (IC10b) provides the 1.5 times gain.

To understand how the rectification works, refer to Figs.4 & 5; A to E in Fig.5 correspond to the waveforms at the identically labelled parts of the circuit in Fig.4.

Consider the operation using a 2V peak-to-peak sinewave at point 'A'. This makes the description easier since the waveform has a peak voltage of 1V. Rectification of the negative and positive waveforms will be described separately.

For the negative half of the cycle, the signal applied to the non-inverting pin 3 input of IC10a via the 15kΩ resistor will cause the voltage at that pin (point B) to be clamped at around -0.3V due to IC10a's internal input protection diode.

The output of IC10a (point C) therefore sits at 0V during negative portions of the cycle, since its negative supply rail is at 0V, and it cannot pull its output lower than that.

IC10b adjusts its output (point E) so that the voltage at its inverting input pin 6 (point D) matches the voltage at non-inverting input pin 5 (point C). Since the 10kΩ resistor from point D to ground has no voltage across it, it

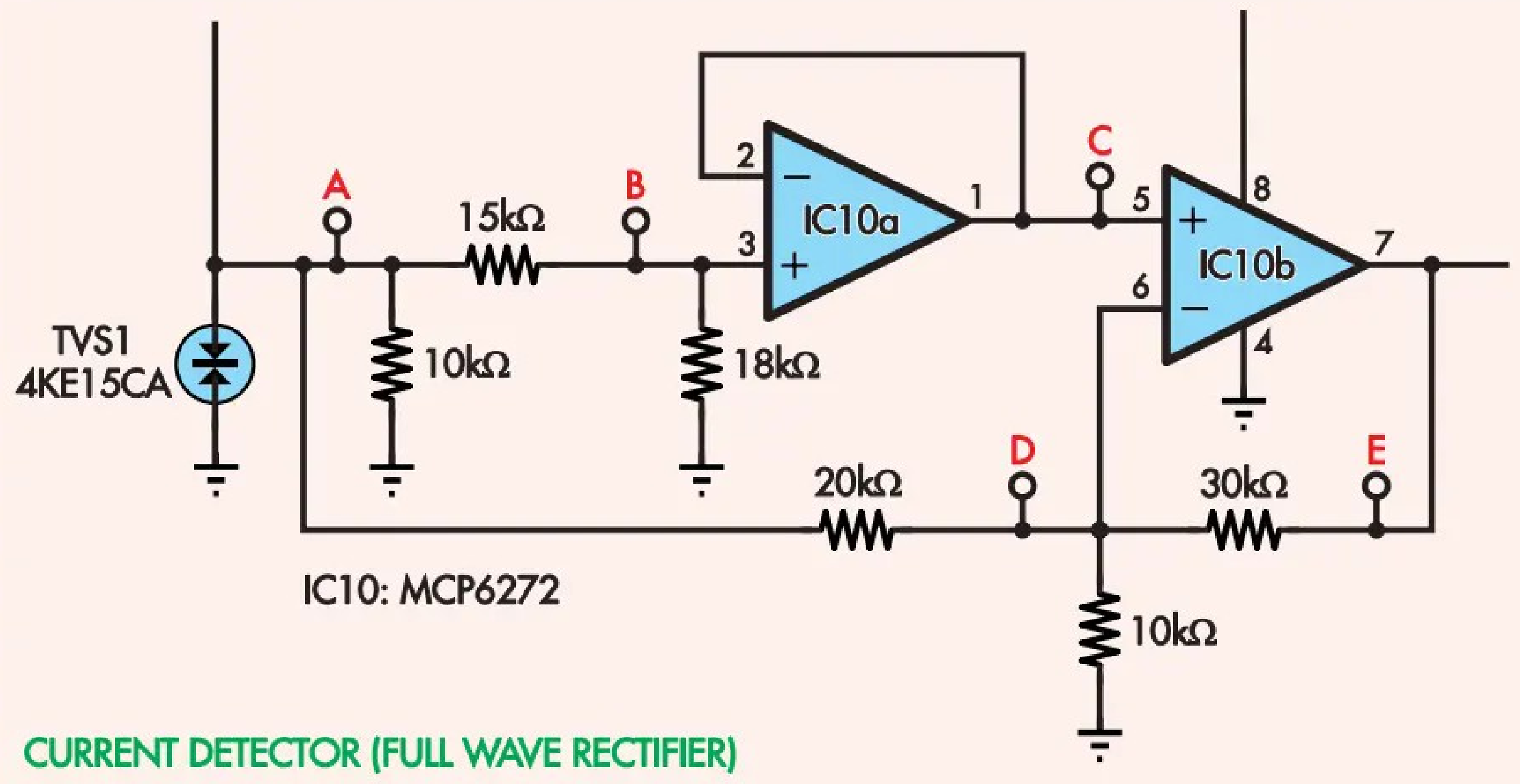


Fig.4: a subsection of the circuit shown in Fig.3, responsible for rectifying the output of current sense transformer T1.

plays no part in the circuit during the negative portions of the cycle.

With the 10kΩ resistor essentially out of the circuit, IC10b operates as a standard inverting amplifier with both inputs (points C and D) at 0V. Its gain is therefore -30kΩ divided by 20kΩ, which equals -1.5 times. So, the -1V peak of the waveform is amplified and inverted to produce +1.5V at point E.

Rectifying positive voltages

The way it works for a positive voltage at the input (point A) is more complicated. Firstly, the voltage at pin 3 (point B) is reduced compared to the 1V peak at the input. That is because of the divider formed by the 15kΩ and 18kΩ resistors, so the voltage becomes 0.5454V (1V × 15kΩ ÷ [15kΩ + 18kΩ]).

Point C will also peak at 0.5454V since IC10a is working as a unity-gain buffer, producing the same voltage at its output as its non-inverting input. Once again, op amp IC10b adjusts the output voltage (point E) so that the voltage at the inverting input at pin 6 (point D) matches the voltage at the non-inverting input, pin 5 (point C).

We know that point D is at 0.5454V, so the current through the 10kΩ resistor to ground is 54.54µA (0.5454V ÷ 10kΩ). With point A at 1V, there is 22.73µA [(1V – 0.5454V] ÷ 20kΩ) flowing in through the 20kΩ resistor. That leaves 31.82µA (54.54µA - 22.73µA) to flow from output pin 7 of IC1b and through the 30kΩ resistor.

Therefore, the voltage across the 30kΩ resistor is 0.9546V (31.82µA x 30kΩ). With point D at 0.5454V, point E must be at 1.5V (0.5454V + 0.9546V).

So, the circuit operates as a full-wave rectifier with a gain of 1.5. The degree of precision depends on the op amp parameters and resistor tolerances. The lower the offset voltage of the op amp and the lower the op amp input bias current, the more accurate the full-wave rectification will be, particularly at low signal levels.

Fortunately, we are not overly concerned with absolute accuracy here. We just need full-wave rectification of the incoming AC signal from the current transformer that works down into the tens of millivolts range. This circuit is more than capable of that.

Scope 3 shows the operation of the full-wave rectifier for a 1V peak (2V peak-to-peak) sinewave at the input to the full wave rectifier (point A) on channel one, shown in yellow.

The channel two cyan waveform is the full-wave rectified waveform (point E). That measures as a 1.48V peak output waveform at 100Hz, compared to 1V peak at 50Hz for the input sinewave. The 20mV discrepancy from the expected 1.5V is due to tolerances in the 1% resistors and the accuracy of the oscilloscope readings.

A 2.2kΩ resistor and 10µF capacitor filter the rectified waveform to produce a smoothed DC voltage suitable for IC9 to monitor via its AN4 analog input (pin 16) and internal analog-to-digital converter (ADC).

Power supply

Power for circuitry is derived directly from the mains via the IEC connector, CON5. A 470nF X2 mains-rated safety capacitor transfers charge each half cycle to a 1000µF capacitor via bridge rectifier BR1. Zener diode ZD1 clamps the voltage to 5.1V.

The supply can be visualised as rectifying a current-limited version of the mains waveform via the series impedance of the 470nF capacitor. The impedance at 50Hz is 6.77kΩ (1 ÷ [470nF × 2π × 50Hz]). The current that can be drawn is equal to the mains voltage (230VAC) divided by the impedance, or about 34mA.

As mentioned earlier, it takes around 8mA to drive all four optos continuously, leaving plenty of overhead for the microcontroller and other components.

The 1kΩ 1W resistor in series with the 470nF capacitor limits the surge current through the capacitor when power is first applied, especially if power is switched when the mains is at a high instantaneous voltage when the switch is thrown. The 1MΩ 1W resistor across the capacitor discharges it when power is off. LED5 connects in series with a 1.5kΩ resistor to indicate when power is on.

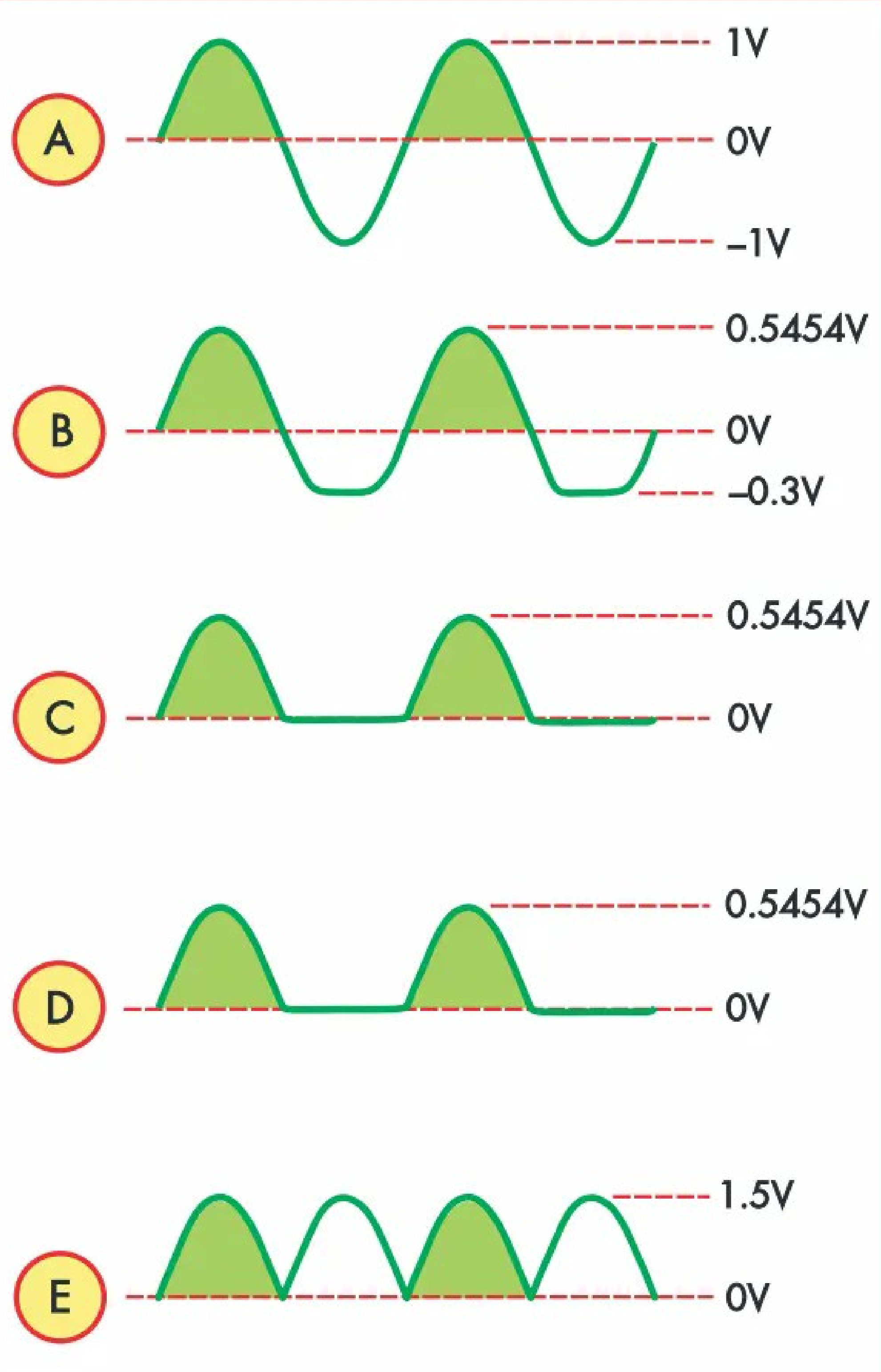
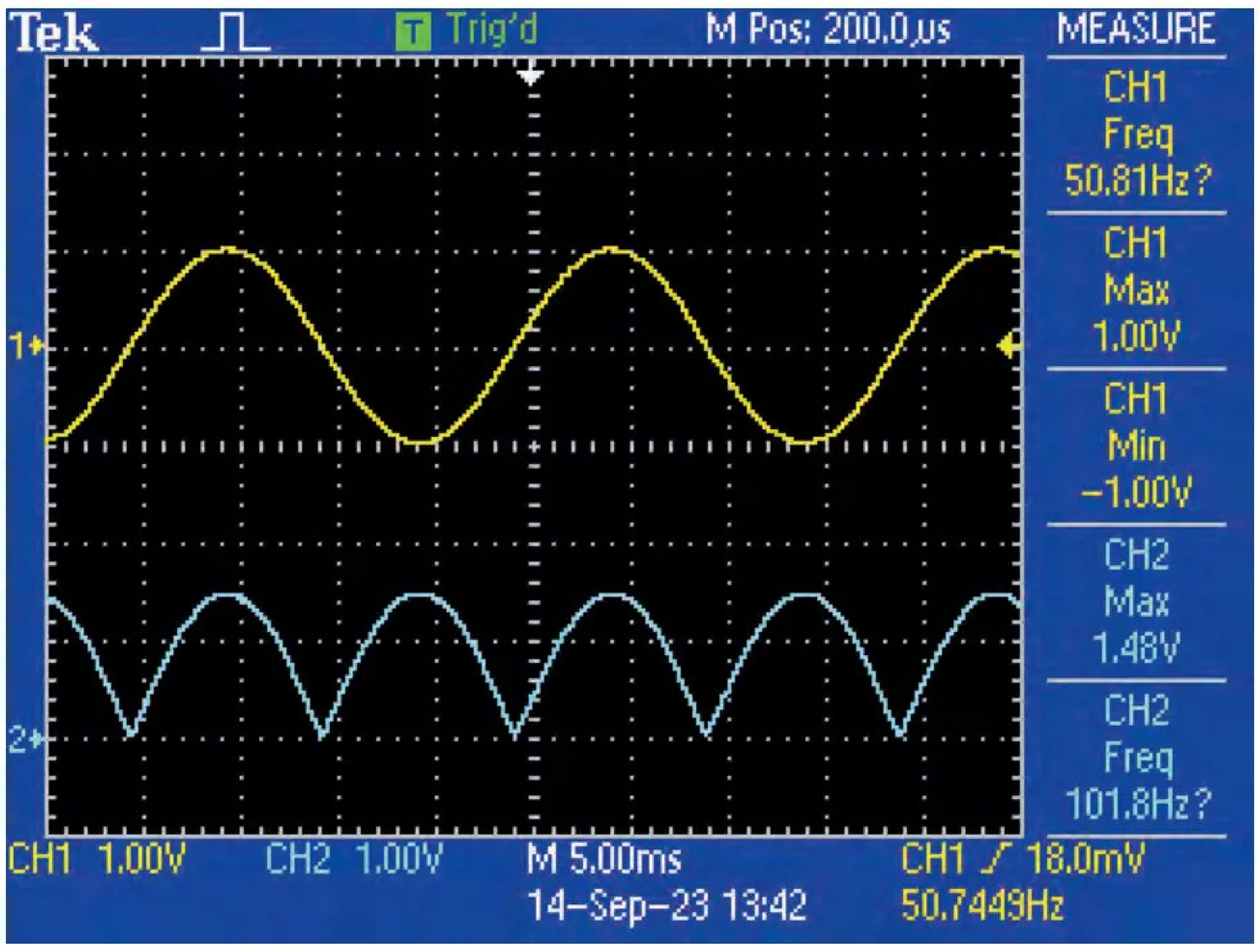


Fig.5: the expected waveforms at points A-E on the circuit (Fig.4) for a 1V peak sinewave from transformer T1. The output (E) is a rectified version of the input (A) but 50% higher in amplitude.

IC9 and IC10 include bypass capacitors to stabilise their 5.1V supplies, with IC9 having a 10µF & 100nF capacitor while IC10 has a 10µF capacitor.

Next month

Having described how the Mains Power-up Sequencer works, we have run out of space in this issue. The final follow-up article next month will cover building it, testing it and setting it up. PE



Scope 3: the measured input (A) and output (E) waveforms of the precision rectifier circuitry with a resistive load, giving a sinusoidal current waveform. You can see how perfectly the input is rectified; using diodes for rectification (unless used within a precision rectifier) would not work this well (if at all) with such low voltages.

DOWNLOAD PE/EPE BACK ISSUES

COMPLETE-YEAR collections – all 12 issues for each year!

From just £5.95 each

VOL 28 – January to December 1999 – **£5.95**
VOL 29 – January to December 2000 – **£6.95**
VOL 30 – January to December 2001 – **£7.95**
VOL 31 – January to December 2002 – **£7.95**
VOL 32 – January to December 2003 – **£7.95**
VOL 33 – January to December 2004 – **£7.95**
VOL 34 – January to December 2005 – **£8.95**
VOL 35 – January to December 2006 – **£8.95**
VOL 36 – January to December 2007 – **£8.95**
VOL 37 – January to December 2008 – **£8.95**
VOL 38 – January to December 2009 – **£10.95**
VOL 39 – January to December 2010 – **£11.95**
VOL 40 – January to December 2011 – **£12.95**
VOL 41 – January to December 2012 – **£14.95**
VOL 42 – January to December 2013 – **£15.95**
VOL 43 – January to December 2014 – **£16.95**
VOL 44 – January to December 2015 – **£17.95**
VOL 45 – January to December 2016 – **£19.95**
VOL 46 – January to December 2017 – **£22.95**
VOL 47 – January to December 2018 – **£27.95**
VOL 48 – January to December 2019 – **£27.95**
VOL 49 – January to December 2020 – **£29.95**
VOL 50 – January to December 2021 – **£32.95**
VOL 51 – January to December 2022 – **£34.95 – NEW!**
VOL 52 – January to December 2023 – **£34.95 – NEW!**

FIVE-YEAR collections – 60 issues!

From just £14.95 each

PE2832: Jan 99 to Dec 03 – £14.95
PE2933: Jan 00 to Dec 04 – £14.95
PE3034: Jan 01 to Dec 05 – £14.95
PE3135: Jan 02 to Dec 06 – £14.95
PE3236: Jan 03 to Dec 07 – £14.95
PE3337: Jan 04 to Dec 08 – £14.95
PE3438: Jan 05 to Dec 09 – £19.95
PE3539: Jan 06 to Dec 10 – £25.95
PE3640: Jan 07 to Dec 11 – £25.95
PE3741: Jan 08 to Dec 12 – £25.95
PE3842: Jan 09 to Dec 11 – £33.95
PE3943: Jan 10 to Dec 14 – £33.95
PE4044: Jan 11 to Dec 15 – £33.95
PE4145: Jan 12 to Dec 16 – £35.95
PE4246: Jan 13 to Dec 17 – £37.95
PE4347: Jan 14 to Dec 18 – £38.95
PE4448: Jan 15 to Dec 19 – £39.95
PE4549: Jan 16 to Dec 20 – £42.95
PE4650: Jan 17 to Dec 21 – £44.95
PE4751: Jan 18 to Dec 22 – £44.95 – NEW!
PE4852: Jan 19 to Dec 23 – £44.95 – NEW!

20 YEARS OF PE!

AMAZING BUNDLE OFFER
Every issue from 1999 – 2018

240 magazines for just

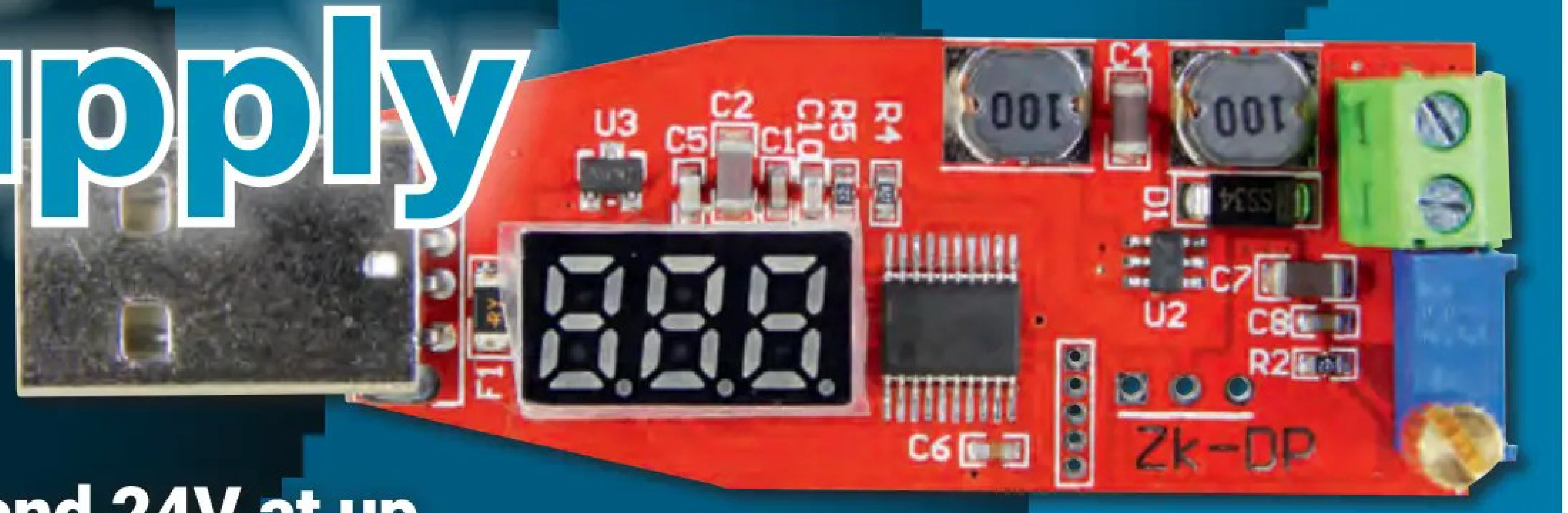
£59.95

PE2832: Jan 99 to Dec 03
PLUS!
PE3337: Jan 04 to Dec 08
PLUS!
PE3842: Jan 09 to Dec 13
PLUS!
PE3447: Jan 14 to Dec 18

Download your collections at: www.electronpublishing.com

Using Electronic Modules with Jim Rowe

1-24V Adjustable USB Power Supply



The "Zk-DP" is a surprisingly inexpensive supply module that converts 5V DC from a USB port into any DC voltage between 1V and 24V at up to 3W. It features a three-digit LED display showing the output voltage, plus easy adjustment of the output voltage with a built-in multi-turn potentiometer.

A lot of small electronic devices now run from low-voltage DC. Luckily, many can run from a 5V DC supply, so they can be powered from a USB port on your computer, a standard 5V USB mains power supply or a portable battery bank.

But things are not so easy if a device needs a supply of 9V, 12V, 15V, or 24V DC (or another 'oddball' value). Usually, you must provide a separate power supply or plugpack to deliver the required voltage.

In those cases, it would be handy to have a small, low-cost power conversion device that could take the power from a standard 5V USB power source and convert it into one of those other voltages.

That's precisely the function of the module we're looking at this month. It plugs directly into a USB-A socket providing 5V DC and can then power a device at any voltage between 1V and 24V DC. Despite its small size, it can supply in excess of 3W of power at any of those output voltages, eg, 250mA @ 12V.

Setting the desired output voltage is very easy, using a built-in multi-turn potentiometer with an attached knob and a tiny three-digit LED display that indicates the current output voltage.

From the legend on the PCB, it is called the Zk-DP Desk Power module, although it would also be correct to call it a DC/DC voltage converter. It's currently available from several online marketplaces at prices ranging from about £2 to £8 plus delivery.

We obtained the unit shown in the photos via AliExpress from a supplier called AGUHAJSU Global Purchase Store for £2.11 plus shipping (a total of just over £3). We noticed that the same unit is also available from eBay.

The Zk-DP module is 70mm long, 26mm wide and 14mm tall (not including the spindle of the voltage adjustment pot). All the components are mounted on a small PCB that's 52.5mm long and 21.5mm wide. The USB-A input plug is at one end of the PCB, while the voltage adjustment pot and small 2-way output screw terminal block are at the other.

All the electronics are housed in a snap-together clear blue plastic case, which allows the 3-digit output voltage indication to be easily read through the case.

How it works

Some searching on the internet didn't reveal any circuit details of the Zk-DP. Still, I was able to remove the PCB from the case and glean enough information to produce the block diagram (Fig.1). I was not able to determine the type of microcontroller used as the ID marking on the top of its 20-pin SSOP package had been removed.

The five-pin SIL onboard programming header suggested it might be a Microchip product. However, when we compared numerous AVR and PIC microcontrollers in that package to the pinout used on the board, none matched, so it's probably something else. Luckily, the SX1308 voltage converter chip still had its ID on top of its 6-pin SOT-23 package.

This device, shown just above the centre of Fig.1, is designed as a boost converter. However, it is being used in a slightly different configuration

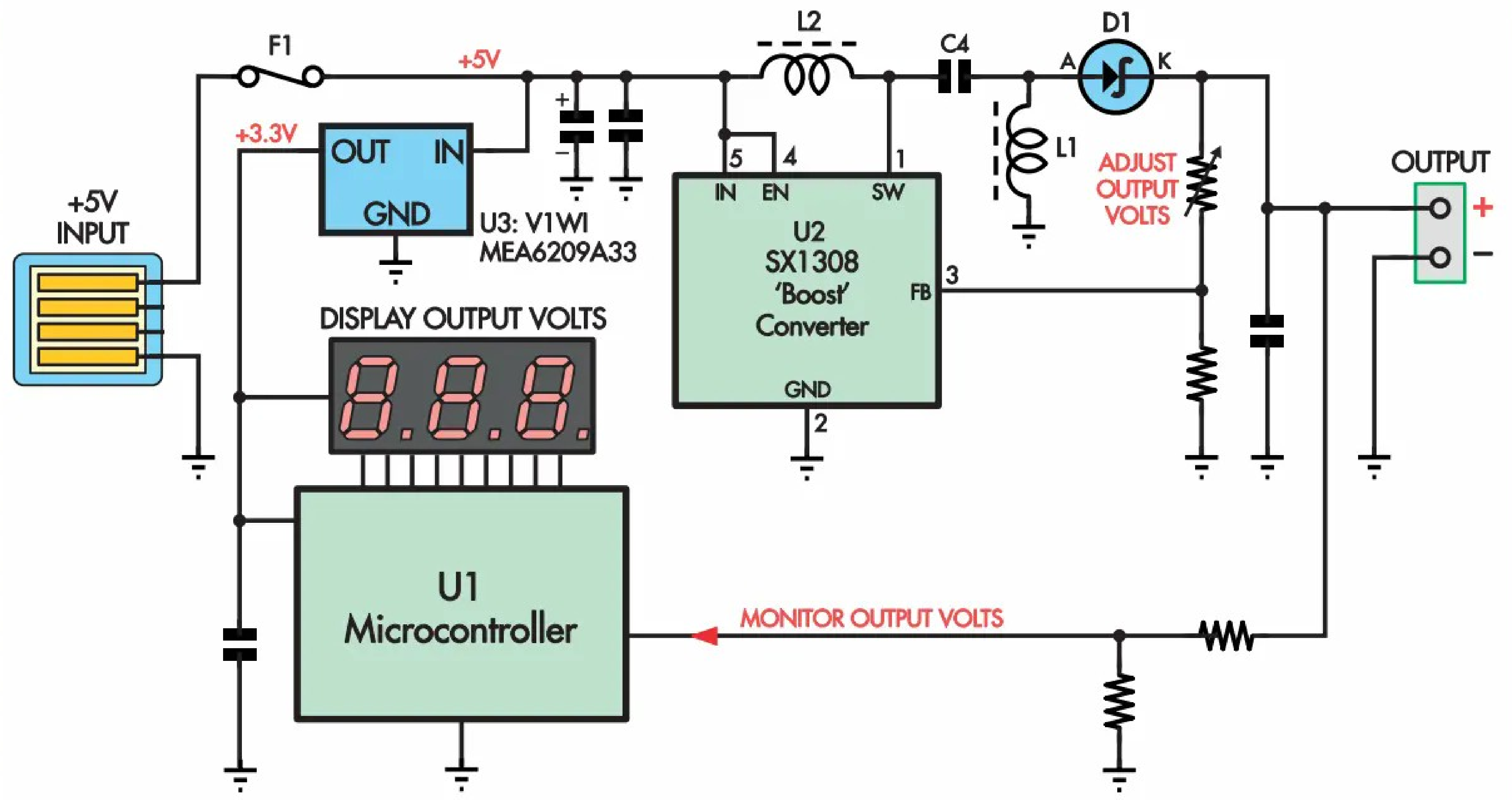
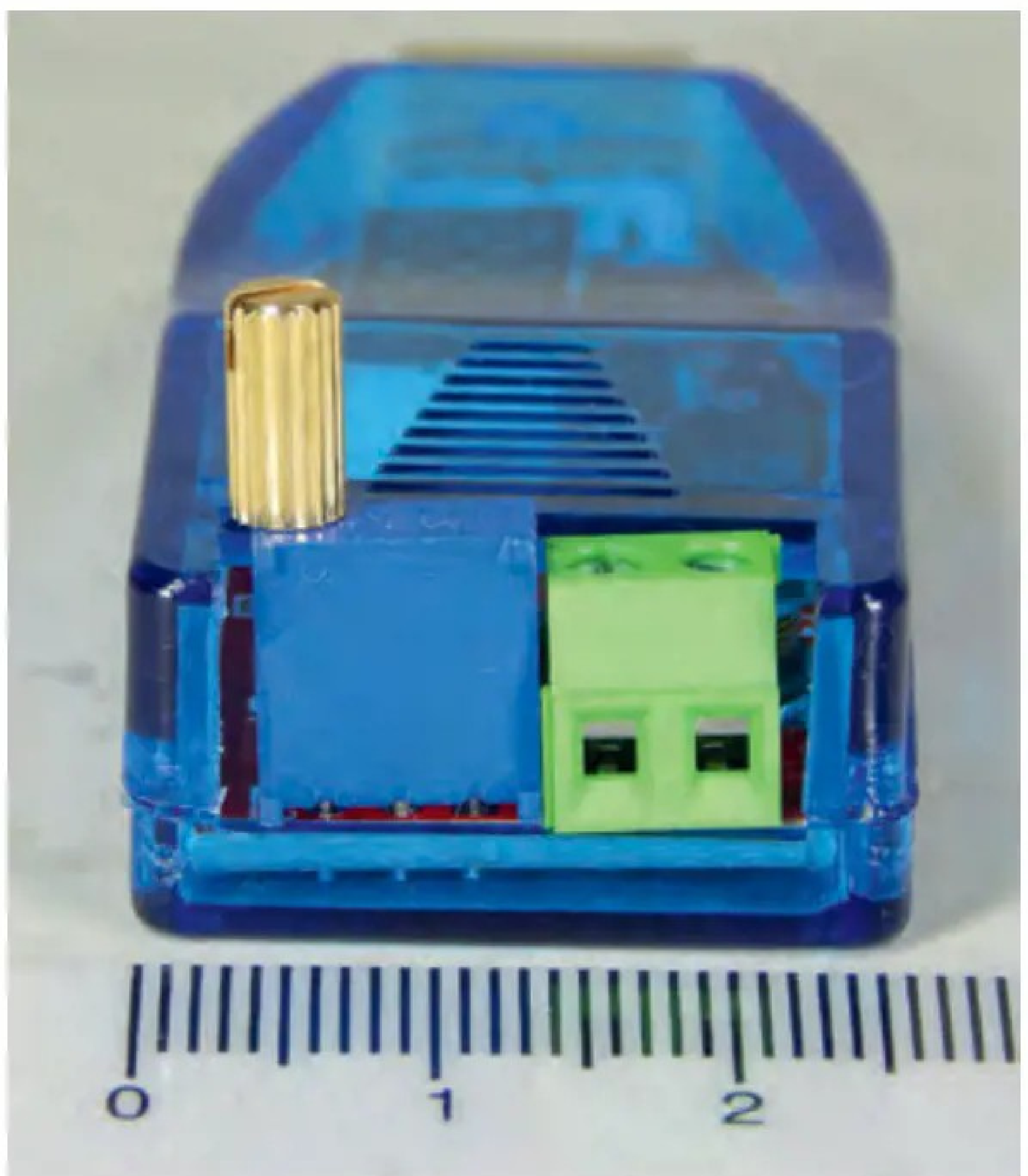
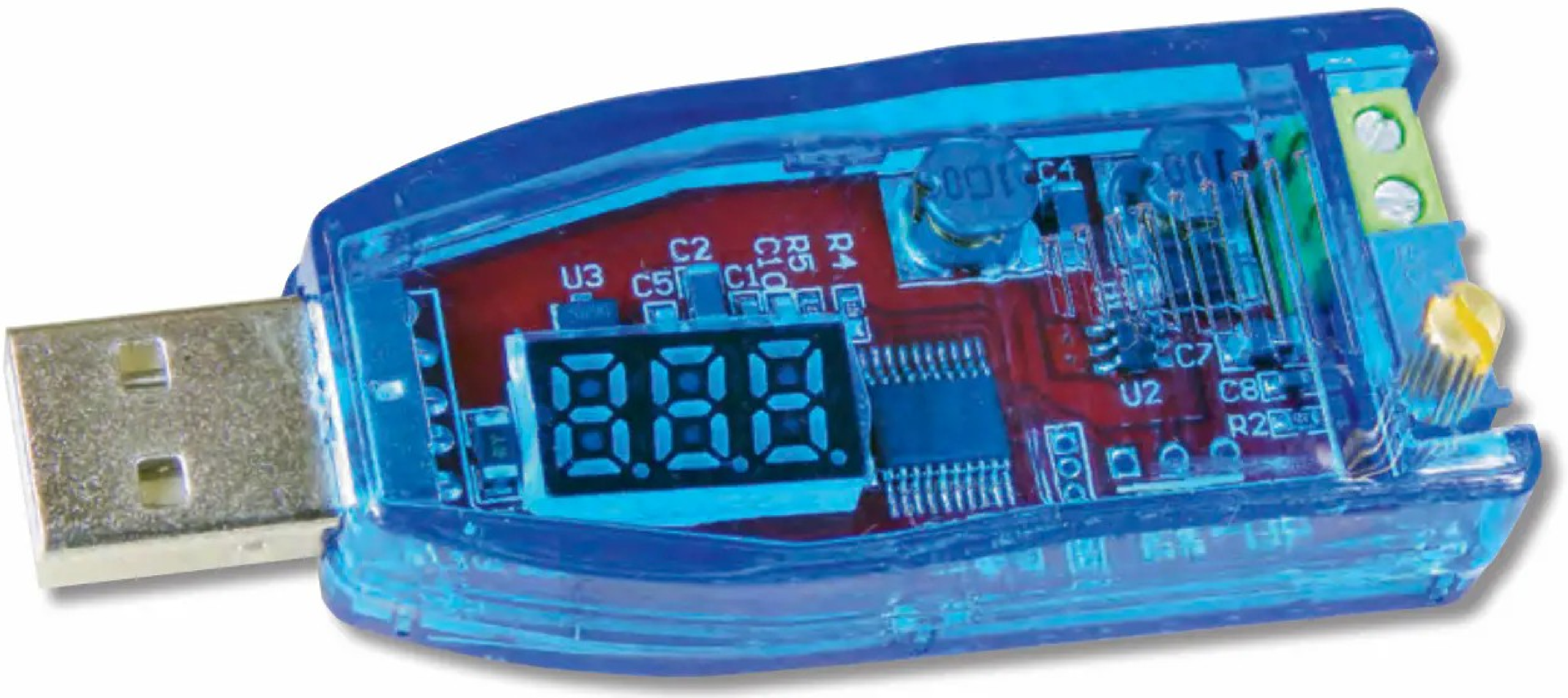


Fig.1: a block diagram for the Zk-DP power supply module. Note that we have not included values for the resistors and capacitors.





These photos show the rear end and general view of the module with the supplied blue plastic case. Note that there is not a cut-out for the 3-digit segment display. Both photos are shown enlarged for clarity.

here, known as a SEPIC converter (single-ended primary-inductor converter). This has a similar function to a buck-boost converter but requires just one switching element instead of two. The operation is described at https://w.wiki/9DjN

An ordinary boost converter (eg, as shown in the SX1308 data sheet) would have a series diode from pin 1 of U2 directly to the output. However, that would mean the output voltage could never go below 5V because there would be a direct path for current to flow from USB +5V through L2 and that diode to the output.

Basically, the series capacitor AC couples the switching waveform to diode D1 so that there is no longer a constant path for current to flow, allowing the output voltage to be regulated below the input as well as above it.

The other inductor, L1, keeps the load current flowing when the internal switch in U2 is closed and no current flows through the series capacitor to the output. That means the output filter capacitor does not have to supply the entire load current during this time, significantly reducing the output voltage ripple.

The SEPIC configuration is related to the Ćuk converter (https://w.wiki/9Db2), except that the positions of the diode and second inductor (L1 here) are swapped. Thus, SEPIC gives a non-inverted output voltage compared to the input. In contrast, the Ćuk converter produces a negative output voltage from a positive input.

The SX1308 runs at a fixed switching frequency of 1.2MHz and uses an internal power Mosfet (with its drain connected to pin 1) as a low-loss switch. The output voltage is adjusted by varying the voltage divider ratio to send a proportion of the output voltage back to pin 3 of the SX1308, its FB (feedback) input.

U2 varies the Mosfet duty cycle in response to changes in the feedback voltage. With a 50% duty cycle, the output voltage is similar to the input voltage of 5V. Higher duty cycles allow the output voltage to go above 5V, while lower duty cycles result in an output below 5V.

The conversion efficiency is quite high because the power Mosfet inside the SX1308 has an on-resistance of only 80mΩ (80 milliohms). For example, when configured as a boost converter and converting between a 5V input and a 12V output, its efficiency for load currents between 100mA and 400mA is better than 92%.

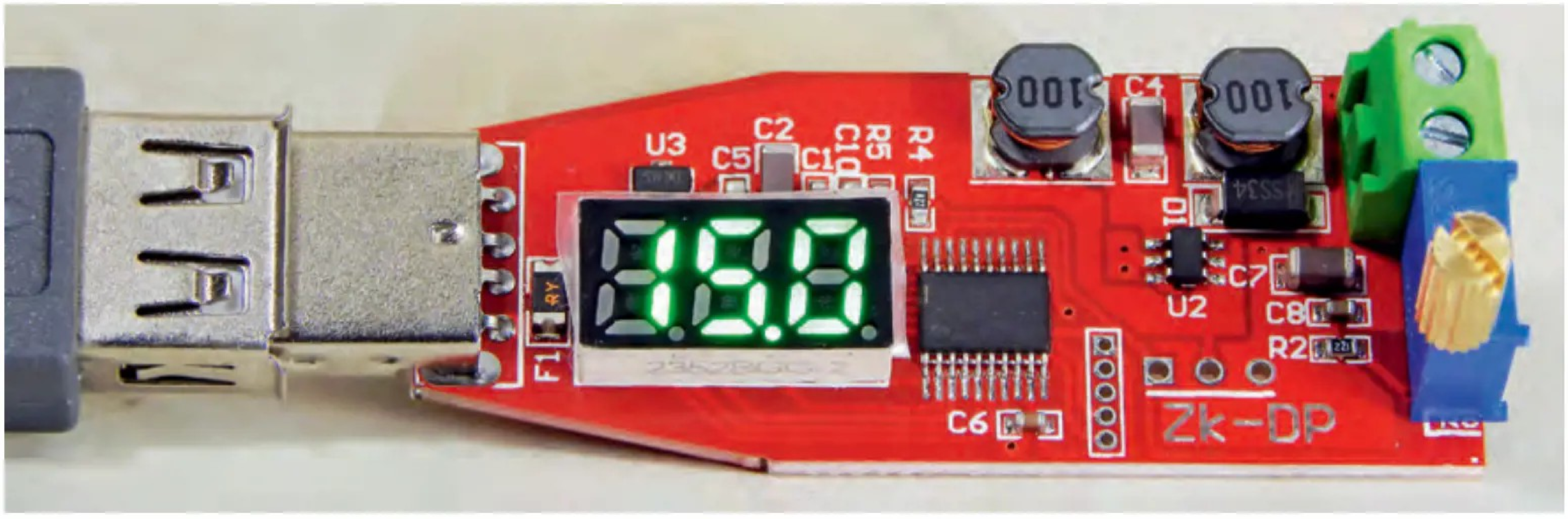
The microcontroller's main job in the Zk-DP module is to measure the output voltage and show it on the small 3-digit LED display. The LED digits are 6mm high and are quite readable.

Trying it out

After connecting the Zk-DP module to a bench power supply capable of providing well over 3W, I also fired up my bench DMMs and connected them to the module's output. I used one to measure the module's output voltage, while the other measured the current it delivered to a programmable DC load. I used a third DMM to monitor the input voltage to the module.

Using this setup, I could test the module's performance at various output voltages for a range of output currents at each voltage level. The results are summarised in Fig.2.

The red horizontal lines show the module's output current at the nine voltage settings I used for testing: 24V, 18V, 15V, 12V, 9V, 7.5V, 5V, 3.3V and 2.5V. The dashed pink curve shows the module's rated maximum output power of 3W.



An example photo showing what the voltage display looks like when powered on, here it is supplying 15.0V.

The output voltage at each setting remained essentially constant for current levels beyond that corresponding to 3W of output power; there was no ‘drooping’ on any of the voltage plots. The voltage level at the 24V setting remained within 30mV up to a load of 200mA (4.8W!), while the level at the 18V setting was within 45mV up to 300mA (5.4W).

The voltage at the 15V setting remained within 3mV at loads up to 300mA (4.5W); at the 12V setting, it remained within 5mV at loads up to 300mA (3.6W); at the 9V setting, it remained within 5mV at loads up to 400mA (3.6W); and at the 7.5V setting, it remained within 25mV at loads up to 500mA (3.75W).

Its output voltage held up similarly well at the 5V and lower voltage settings, so you can see why the plots in Fig.2 are all shown simply as horizontal lines.

Although I tested the module’s performance beyond the 3W limit, that was only for brief periods. I would not recommend using the module to deliver more than 3W for more than short periods to prevent it from overheating and possibly being damaged.

The next test I ran on the module was to check the accuracy of its LED voltage display at various output voltage settings. Here again, it performed well, as shown in Fig.3.

The readout error was highest at 2.5V, at +1.2%, then varied between -0.2% and +0.8% before rising to +0.5% at 12V, then falling to -0.3%, -0.1% at 18V and 20V, and then to -0.6% at 24V. So, using the module’s LED display to set its output voltage gets you pretty close.

The error percentages provided are best-case values, an additional error of up to 100mV is possible due to display rounding.

Conclusion

There is little more to say about this tiny low-voltage voltage conversion module. It is nicely made, performs surprisingly well and carries a very small price tag.

You could use it to power a small breadboard during development from a conveniently nearby computer, or any other time you need a stable DC voltage at a modest current level. Adding it to a USB power bank makes a handy portable, adjustable DC voltage source. **PE**

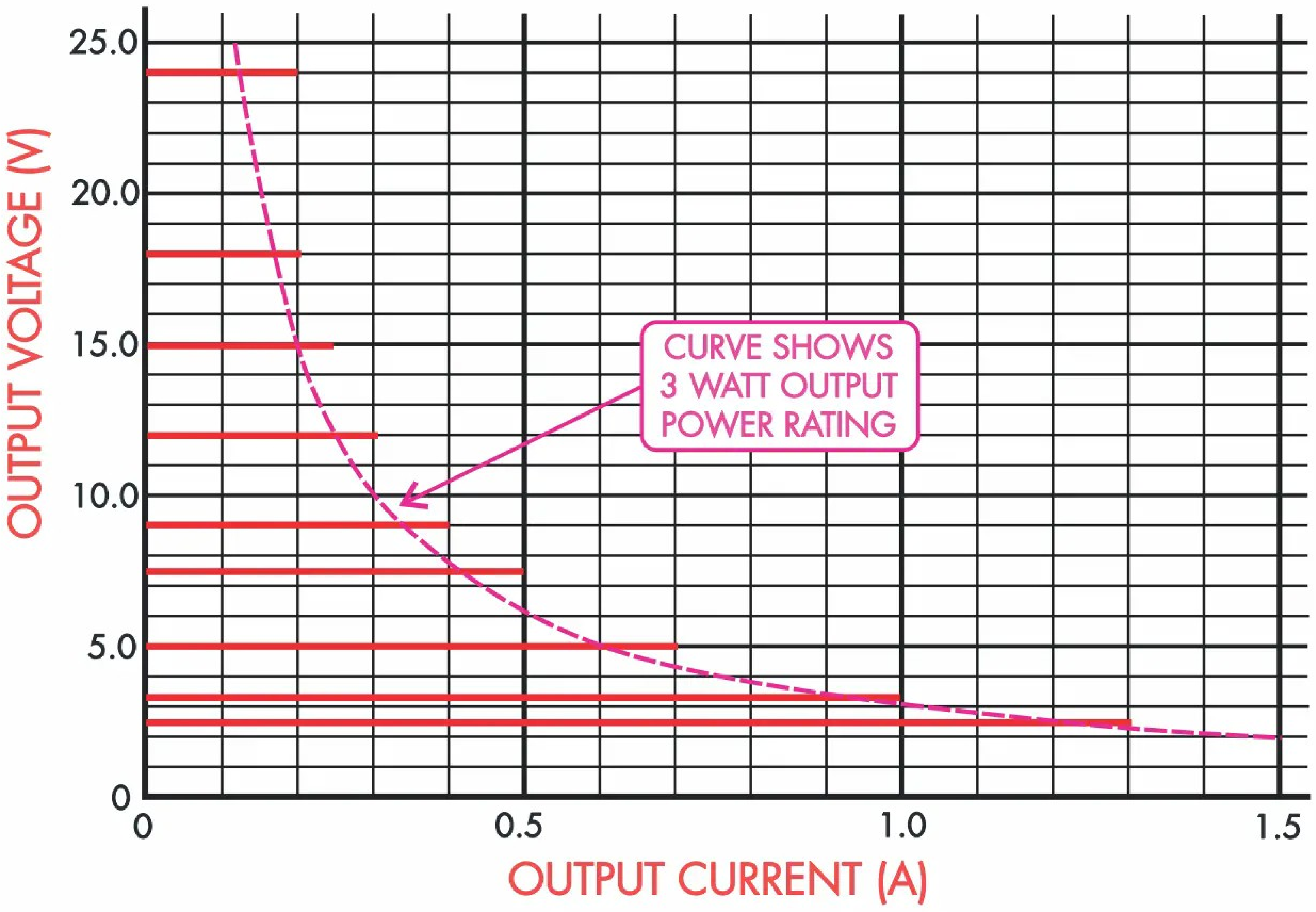


Fig.2: this graph shows how the Zk-DP power supply module performed at various voltages for different output currents.

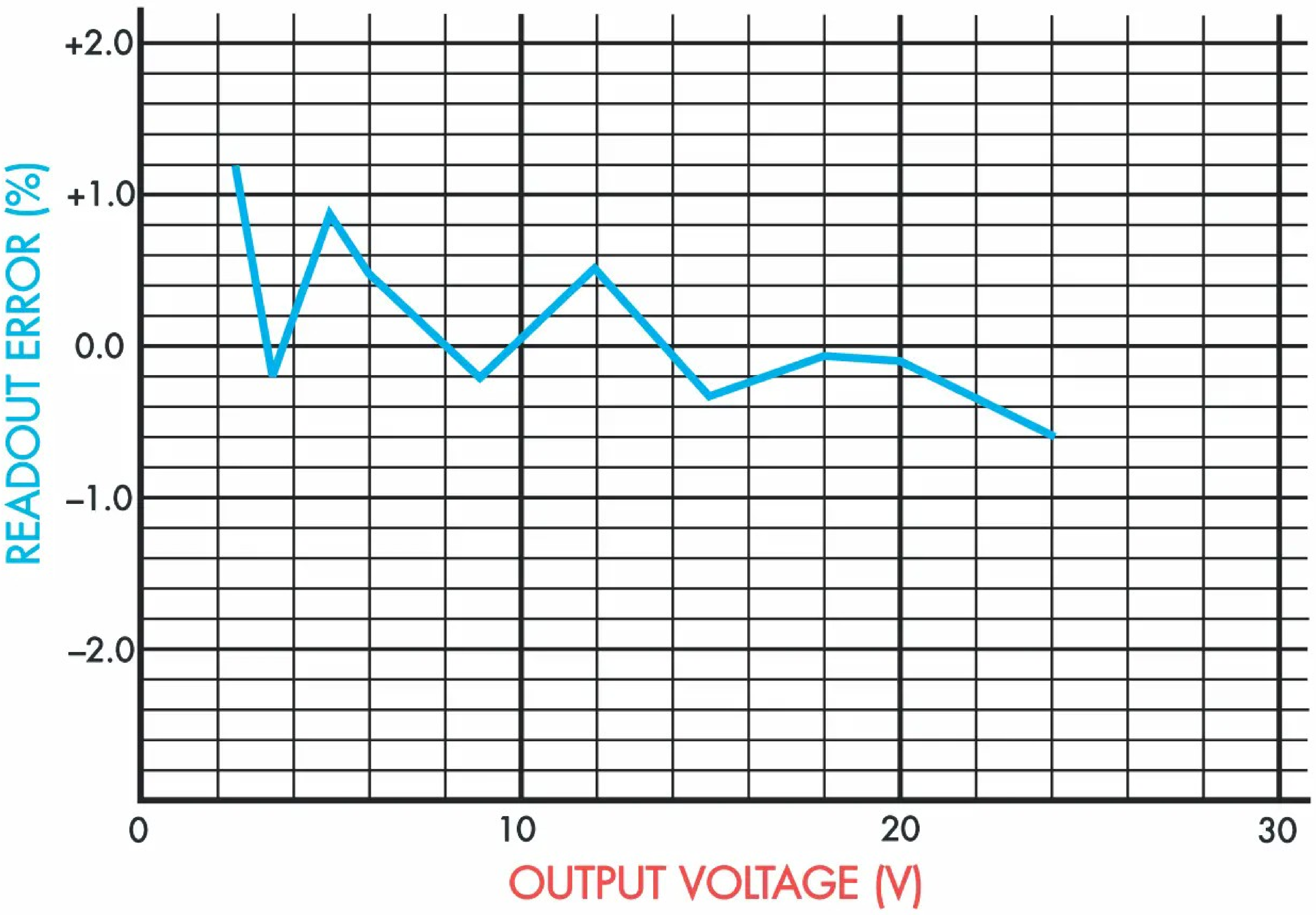
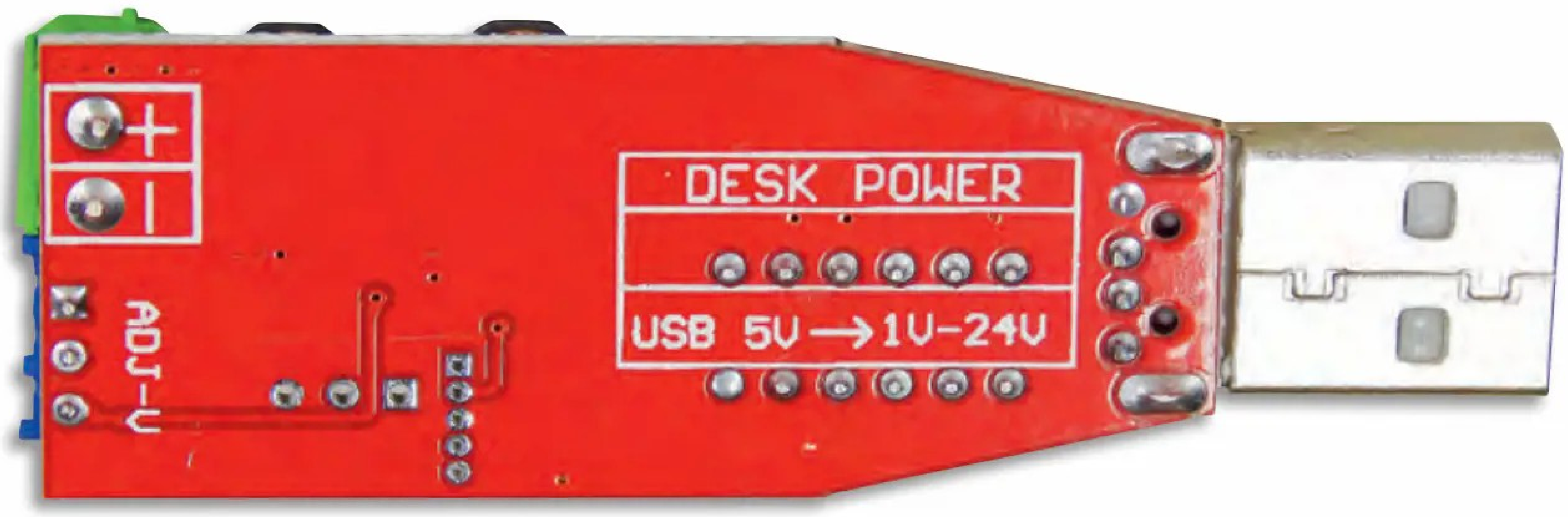


Fig.3: this graph shows the difference between the selected output voltage and the voltage displayed on the 3-digit segment display.



There’s nothing of importance on the underside of the module, although this is the only place that the output polarity is clearly indicated.

Practical Electronics PCB SERVICE

PROJECT	CODE	PRICE
FEBRUARY 2025		
Laser Communicator transmitter	16102241	£3.99
Laser Communicator receiver	16102242	£3.99
Model Railway Points Controller transmitter	09101241	£3.99
Model Railway Points Controller receiver	09101242	£2.99
Mains Power-Up Sequencer	10108231	£11.99
JANUARY 2025		
USB to PS/2 Converter for VGA PicoMite	07111231	£3.99
ps2x2pico USB to PS/2 Converter	07111232	£3.99
Compact Microphone Preamplifier (case version)	01110231	£5.99
Compact Microphone Preamplifier (integrated version)	01110232	£5.99
DECEMBER 2024		
Raspberry Pi Clock Radio PCB pair	19101241/2	£12.99
VGA PicoMite (blue)	07107221	£5.99
Secure Remote Switch receiver	10109231	£4.99
Secure Remote Switch transmitter (module version)	10109232	£2.99
Secure Remote Switch transmitter (discrete version)	10109233	£2.99
NOVEMBER 2024		
Ideal Diode Bridge Rectifiers (28mm square)	18101241	£3.99
Ideal Diode Bridge Rectifiers (22mm square)	18101242	£3.99
Ideal Diode Bridge Rectifiers (4-pin SIL)	18101243	£3.99
Ideal Diode Bridge Rectifiers (tiny SOT-23)	18101244	£3.99
Ideal Diode Bridge Rectifiers (standalone SMD)	18101245	£4.99
Ideal Diode Bridge Rectifiers (standalone TH; 2oz copper)	18101246	£6.99
Multi-channel Volume Control (volume PCB)	01111221	£4.99
Multi-channel Volume Control (control PCB)	01111222	£4.99
Multi-channel Volume Control (OLED PCB, black)	01111223	£4.99
OCTOBER 2024		
TQFP-32 Programming Adaptor	24108231	£4.99
TQFP-44 Programming Adaptor	24108232	£4.99
TQFP-48 Programming Adaptor	24108233	£4.99
TQFP-64 Programming Adaptor	24108234	£4.99
2m VHF FM Test Signal Generator	06107231	£4.99
SEPTEMBER 2024		
Calibrated Microphone (SMD version)	01108231	£3.99
Calibrated Microphone (TH version)	01108232	£3.99
PIC Programming Adaptor	24105231	£4.99
Salad Bowl Speaker crossover	01109231	£7.99
AUGUST 2024		
Arduino ESR Meter combined L/C-ESR	04106182	£9.99
Arduino ESR Meter separate ESR	04106183	£7.99
Watering System Controller	15110231	£11.99
JULY 2024		
Dynamic NFC Tag (22 × 31mm)	06101231	£5.95
Dynamic NFC Tag (86 × 54mm)	06101232	£7.95
Reciprocal Frequency Counter	CSE230101C	£8.95
Reciprocal Frequency Counter front panel (black mask)	CSE230102	£7.95
Pi Pico-based Thermal Camera	04105231	£6.95
JUNE 2024		
Loudspeaker Test Jig	04106231	£12.95
MAY 2024		
GPS-Disciplined Oscillator	04103231	£12.95
Dual RF Amplifier	CSE220602A	£5.95
Songbird	08103231	£7.95

PROJECT	CODE	PRICE
APRIL 2024		
Basic RF Signal Generator	CSE221001	£8.99
Basic RF Signal Generator front panel (black solder mask)	CSE220902B	£9.99
Silicon Chirp Cricket	08101231	£7.99
Test Bench 'Swiss Army Knife'	04110221	£9.99
MARCH 2024		
Digital Volume Control Potentiometer SMD version	01101231	£8.95
Digital Volume Control Potentiometer through-hole version	01101232	£9.95
Advanced SMD Test Tweezers body	04106221	£6.95
Advanced SMD Test Tweezers legs (pair)	04106212	£7.95
FEBRUARY 2024		
Active Mains Soft Starter	10110221	£10.95
JANUARY 2024		
Q Meter	CSE220701	£8.95
Q Meter front panel (black solder mask)	CSE220704	£7.95
Raspberry Pi Pico W BackPack	07101221	£8.95
DECEMBER 2023		
Digital Boost Regulator	24110224	£8.95
Dual-Channel Power Supply for Breadboards	04112221	£11.95
Display Adaptor for the Breadboard PSU	04112222	£9.95
NOVEMBER 2023		
LC Meter Mk3	CSE220503C	£9.95
DC Supply Filter for vehicles	08108221	£8.95
Discrete Audio Op Amp PCB	AO1-JUL23	£9.95
Discrete Audio Op Amp PCB + essential components	AO2-JUL23	£17.95
OCTOBER 2023		
Buck/Boost Charger Adaptor	14108221	£9.95
PIC Breakout Board for SOIC parts	24110225	£5.95
PIC Breakout Board for DIP parts	24110222	£5.95
AVR64DD32 Breakout board	24110223	£5.95
Automatic Train Controller	09109221	£6.95
Chuff Sound module	09109222	£6.95
SEPTEMBER 2023		
Mini LED Driver	16106221	£7.95
New GPS-Synchronised Clock	19109221	£9.95
AUGUST 2023		
110dB RF Attenuator	CSE211003	£9.95
Universal Battery Charge Controller (2023 update)	14107192	£9.95
Wide-Range OhmMeter	04109221	£12.95
JULY 2023		
Multimeter Checker/Calibrator	04107221	£10.95
JUNE 2023		
Arduino Programmable Load	04105221	£8.95
Buck-Boost LED Driver	16103221	£8.95
MAY 2023		
Precision AM-FM DDS Signal Generator	CSE211002	£14.95
Improved SMD Test Tweezers programmed PIC	0410621PIC	£12.95
AO 2x-dual-to-quad through-hole (pack of five)	AO1-MAY23	£6.95
AO 2x-dual-to-quad SMD (pack of five)	AO2-MAY23	£6.95
AO 2x-single-to-dual through-hole (pack of five)	AO3-MAY23	£6.95
AO 2x-single-to-dual SMD (pack of five)	AO4-MAY23	£6.95

PCBs for most recent *PE/EPE* constructional projects are available. From the July 2013 issue onwards, PCBs with eight-digit codes have silk screen overlays and, where applicable, are double-sided, have plated-through holes, and solder mask. They are similar to photos in the project articles. Earlier PCBs are likely to be more basic and may not include silk screen overlay, be single-sided, lack plated-through holes and solder mask.

Always check price and availability in the latest issue or online. A large number of older boards are listed for ordering on our website.

In most cases we do not supply kits or components for our projects. For older projects it is important to check the availability of all components before purchasing PCBs.

Back issues of articles are available – see Back Issues page for details.

Double-sided | plated-through holes | solder mask

PROJECT	CODE	PRICE
APRIL 2023		
500W Amplifier Module	see p.22, April 2023	
Clipping Indicator (per channel)	01112211	£7.95
CD Welder Power Supply (one needed)	29103221	£9.95
CD Welder Controller (one needed)	29103222	£9.95
CD Welder Energy Storage module (several needed)	29103223	£7.95
AO Universal Dual Op Amp Board	AO1-APR23	£9.95
AO Stereo RIAA precision passives kit for dual op amp	AO2-APR23	£8.95
MARCH 2023		
Pico BackPack	07101221	£9.95
Semaphore Signal (controller)	09103221	£7.95
Semaphore Signal (blade)	09103222	£5.95
FEBRUARY 2023		
Tesla Coil driver board	26102221	£9.95
Tesla Coil potentiometer board	26102222	£5.95
Cooling Fan Controller & Loudspeaker Protector	01102221	£8.95
Remote Gate Controller	11009121	£12.95
JANUARY 2023		
Classic LED Metronome – 8-LED	23111211	£7.95
Classic LED Metronome – 10-LED	23111212	£8.95
Multi-Channel Speaker Protector – 6 channel	01101221	£9.95
Multi-Channel Speaker Protector – 4 channel	01101222	£7.95
Remote Control Range Extender – IR-to-UHF	15109212	£5.95
Remote Control Range Extender – UHF-to-IR	15109211	£7.95
AO Universal Single Op Amp Board	AO1-JAN23	£7.95
DECEMBER 2022		
Hummingbird Amplifier	01111211	£9.95
SMD Trainer PCB	29106211A	£8.95
SMD Trainer PCB + parts	29106211B	£13.95
NOVEMBER 2022		
USB Cable tester – main PCB	04108211	£12.95
USB Cable tester – front panel	04108212	£5.95
USB Cable tester – optional panel	SC5970	£5.95
Model Railway Carriage Lights – PCB	09109211	£6.95
AO trnsfmr PCB – standard VTX-A range	VTX-101-007	£6.95
AO trnsfmr PCB – dual-outline VTX102-3001/101-3002	VTX-Dual	£6.95
OCTOBER 2022		
SMD Test Tweezers – PCB and pair of tweezer arms	04106211-2	£11.95
SMD Test Tweezers – programmed PIC12F1572-I/SN	0410621A	£7.95
Tele-com	12110211	£12.95
SEPTEMBER 2022		
Touchscreen Digital Preamp – main board	01103191	£12.95
Touchscreen Digital Preamp – adaptor board pair	01103192	£5.95
20A DC Motor Speed Controller	11006211	£9.95
AUGUST 2022		
Multi-purpose Battery Manager – I/O Expander	11104212	£5.95
Multi-purpose Battery Manager – Switch Module	11104211	£8.95
Simple MIDI Music Keyboard (for 8 switches)	23101213	£6.95
Nano Pong	08105212	£7.95
JULY 2022		
Silicon Labs AM/FM/SW Radio	CSE210301C	£10.95
Level Crossing Controller	09108211	£6.95
JUNE 2022		
Full-wave Motor Speed Controller	1010221	£8.95
PIC Programming Helper for 8-pin PICs only	24106211	£7.95
PIC Programming Helper for 8, 14 or 20-pin PICs	24106212	£10.95
Advanced GPS Computer	05102211	£9.95

PROJECT	CODE	PRICE
MAY 2022		
Bus board PCB for Analogue Vocoder	AO1-MAY22	£10.95
Complete set of 14 PCBs for Analogue Vocoder	AO2-MAY22	£97.95
Programmed EEPROM for Digital FX Unit	FX1-MAY22	£10.95
Programmed PIC for Digital FX Unit w/ potentiometer	FX2-MAY22	£8.95
APRIL 2022		
64-key MIDI Matrix shield	23101211	£8.95
64-key MIDI Matrix switch board	23101212	£11.95
High-current Battery Balancer	14102211	£10.95
Digital FX Unit – using potentiometer	01102211	£9.95
Digital FX Unit – using BCD switch	01102212	£9.95
Universal Audio PSU	AO1-APR22	£11.95
MARCH 2022		
Mini Isolated Serial Link	24102211	£5.95
Busy Loo Indicator	16112201	£5.95
Analogue Vocoder – Band-pass filter board	AO1-MAR22	£9.95
Analogue Vocoder – HP/LP filter board	AO2-MAR22	£9.95
FEBRUARY 2022		
Arduino-based Power Supply	18106201	£9.95
Battery Monitor Logger	11106201	£10.95
Electronic Wind Chimes	23011201	£10.95
Analogue Vocoder – Driver Amplifier	AO-FEB22	£8.95

For the many earlier PCBs that we stock please see the PE website: www.electronpublishing.com

PE/EPE PCB SERVICE

Order Code	Project	Quantity	Price

Name ....

Address ....

....

Tel ....

Email ....

Card No ....

Valid From ....Expiry Date ....

Card Security No ....

You can also order PCBs by phone, email or via the shop on our website: www.electronpublishing.com

No need to cut your issue – a copy of this form is just as good!

All prices include VAT and UK p&p. Add £4 per *project* for post to Europe; £5 per *project* outside Europe.

Orders and payment should be sent to:

Practical Electronics, Electron Publishing Ltd
113 Lynwood Drive, Merley, Wimborne, Dorset BH21 1UU
Tel 01202 880299 Email: pe@pemag.au
On-line Shop: www.electronpublishing.com

Sorry, cheques cannot be accepted as we are based in Australia and our UK bank account does not allow cheque deposits.

NOTE: Most boards are in stock and sent within seven days of order receipt. Please allow up to 28 days delivery if we need to restock.

Practical Electronics PCB SERVICE

PROJECT	CODE	PRICE
JANUARY 2022		
Vintage battery Radio Li-ion Power Supply	11111201	£9.95
MiniHeart: A Miniature Heartbeat Simulator	01109201	£8.95
DECEMBER 2021		
AM/FM/SW Digital Receiver	CSE200902A	£13.95
Balanced Input and Attenuator for USB CODEC	01106202	£11.95
NOVEMBER 2021		
Dual Battery Lifesaver	11111202	£6.95
OCTOBER 2021		
Mini Wi-Fi LCD BackPack	24106201	£8.95
SEPTEMBER 2021		
USB SuperCodec PCB	01106201	£14.95
Audio DDS Oscillator PCB	01110201	£5.95
Audio DDS Oscillator rotary encoder	01110201-ENC	6.95
Programming Adaptor Board for Audio DDS Oscillator	01110202	£5.95
High-power Ultrasonic Cleaner main PCB	04105201	£14.95
High-power Ultrasonic Cleaner front-panel PCB	04105202	
Night Keeper Lighthouse PCB	08110201	£5.95
AUGUST 2021		
Ol' Timer PCB	19104201	£11.95
Ol' Timer 8x8 RGB LED module using WS2812B	19104201-88	£8.95
Ol' Timer set of acrylic case pieces and spacer	19104201-ACR	£8.75
Ol' Timer DS3231 RTC IC wide SOIC-16	19104201-RTC	£5.95
Wideband Digital RF Power Meter	04106201	£9.75
Switchmode 78xx regulators ***(PACK of 5!)***	18105201	£7.95
Cool Beans SMAD display	CB-AUG21	£11.95
JULY 2021		
ATtiny816 Breakout / Dev Board w/ Capacitive Touch	24110181	£9.75
IR Remote Control Assistant (Jaycar version)	15005201	£8.95
IR Remote Control Assistant (Altronics version)	15005202	£8.95
PIC18F Development Board	PNM-JUL21	£12.95
Microphone Preamplifier	AO-JUL21	£11.95
JUNE 2021		
Roadies' Test Signal Generator (surface-mount ver.)	01005201	£8.95
Roadies' Test Signal Generator (through-hole version)	01005202	£9.95
Touchscreen Wide-range RCL Box (Resistor module)	04104201	£18.95
Touchscreen Wide-range RCL Box (Ind/Cap module)	04104202	
KickStart Part 3 – Gyrator-based Audio Filter	KS3-2021	£7.95
MAY 2021		
7-Band Equaliser (Mono)	01104201	£8.95
7-Band Equaliser (Stereo)	01104202	£10.95
Car Altimeter	05105201	£7.95
APRIL 2021		
Reflow Oven – DSP Active Crossover (CPU)	01106193	£19.95
Reflow Oven – DSP Active Crossover (Front panel)	01106195	
Reflow Oven – DSP Active Crossover (LCD)	01106196	
Frequency Reference Signal Distributor	CSE200103	£8.95
MARCH 2021		
Nutube Guitar Effects Pedal	01102201	£12.95
Programmable Thermal Regulator (Peltier Interface)	21109181	£18.95
Programmable Thermal Regulator (Peltier Driver)	21109182	
Tunable HF Preamp	CSE190502	£8.95
FEBRUARY 2021		
4G Remote Monitoring	27111191	£9.95

PROJECT	CODE	PRICE
JANUARY 2021		
Nutube Valve Preamplifier	01112191	£12.95
Arduino DCC Controller	09207181	£10.95
DECEMBER 2020		
Pseudo-Random Sequence Generator	16106191	£7.95
Clever Charger	14107191	£11.95
PE Theremin Amplifier	AO-1220-01	£8.95
NOVEMBER 2020		
LED Christmas Tree (1 off)	16107181-1	£6.95
LED Christmas Tree (4 off)	16107181-2	£14.95
LED Christmas Tree (12 off)	16107181-3	£24.95
LED Christmas Tree (20 off)	16107181-4	£34.95
USB/SPI Interface Board	16107182	£5.95
45V/8A Power Supply PCB *plus* acrylic spacer	18111181	£14.95
45V/8A Power Supply five-way display bezel	18111181-BZ	£3.95
Five-way LCD Panel Meter/Display	18111182	£7.95
OCTOBER 2020		
Digital Audio Millivoltmeter	04108191	£9.95
Precision Signal Amplifier	04107191	£7.95
SEPTEMBER 2020		
PE Theremin PSU	AO-0920-01	£5.95
PE Theremin PSU transformer	AO-0920-02	£7.95
Micromite Explore-28	07108191	£6.95
Ultrabrite LED Driver	16109191	£6.95
AUGUST 2020		
Micromite LCD BackPack V3	07106191	£9.95
Steering Wheel Audio Button to Infrared Adaptor	05105191	£7.95
JULY 2020		
AM/FM/CW Scanning HF/VHF RF Signal Generator	04106191	£13.95
Speech Synthesiser with the Raspberry Pi Zero	01106191	£5.95
PE Mini-organ PCB	AO-0720-01	£14.95
PE Mini-organ selected parts	AO-0720-02	£8.95
High-current 12V Battery Isolator – control	05106191	£6.95
High-current 12V Battery Isolator FET (2oz)	05106192	£9.95
JUNE 2020		
Arduino breakout board – 3.5-inch LCD Display	24111181	£6.95
Six-input Audio Selector main board	01110191	£10.95
Six-input Audio Selector switch panel board	01110192	
MAY 2020		
Ultra-low-distortion Preamplifier Input Selector	01111112	£11.25
Ultra-low-distortion Preamplifier pushbutton board	01111113	
Universal Regulator	18103111	£7.95
433MHz Wireless Data Repeater	15004191	£8.50
Bridge-mode Adaptor for Amplifier	01105191	£7.95
iCEstick VGA Terminal	02103191	£5.95
Analogue noise with tilt control	AO-0520-01	£7.95
Audio Spectrum Analyser	PM-0520-01	£8.95
APRIL 2020		
Flip-dot Display black coil board	19111181	£14.95
Flip-dot Display black pixels	19111182	
Flip-dot Display black frame	19111183	
Flip-dot Display green driver board	19111184	
MARCH 2020		
Diode Curve Plotter	04112181	£10.95
Steam Train Whistle / Diesel Horn Sound Generator	09106181	£8.50
Universal Passive Crossover (one off)	UPC0320	£12.50

Silicon Chip kits & parts for projects in this issue (posted from Australia):

Model Railway Points Controller transmitter programmed PIC	https://siliconchip.au/Shop/20/6906	AUD $12.00 (about £6) + P&P
Model Railway Points Controller receiver programmed PIC	https://siliconchip.au/Shop/20/6907	AUD $12.00 (about £6) + P&P
Mains Power-Up Sequencer programmed PIC	https://siliconchip.au/Shop/20/6901	AUD $12.00 (about £6) + P&P
Mains Power-Up Sequencer hard-to-get parts (incl. PCB & PIC)	https://siliconchip.au/Shop/20/6871	AUD $114.00 (about £57) + P&P
Mains Power-Up Sequencer current detection add-on parts	https://siliconchip.au/Shop/20/6902	AUD $24.00 (about £12) + P&P

20% VAT is included in the above prices (it will be removed for customers outside the UK). Postage & packing cost is typically around £12-15.
Please allow 1-2 weeks for delivery (longer in some cases).

CLASSIFIED ADVERTISING

Practical Electronics

If you want your advertisements to be seen by the largest readership at the most economical price then our classified page offers excellent value.

The rate for semi-display space is £10 per centimetre high, with a minimum height of 2·5cm. All semi-display advertisements have a width of 5.5cm. The prepaid rate for classified adverts is 40p per word (minimum 12 words).

For rates, further information on display and classified advertising or to book an ad, please email us at pe@pemag.au

Practical Electronics reaches more UK readers than any other UK monthly hobby electronics magazine. Our sales figures prove it.

We have been the leading monthly magazine in this market for the last twenty-seven years.

BOWOOD ELECTRONICS LTD
Suppliers of Electronic Components
www.bowood-electronics.co.uk
Unit 10, Boythorpe Business Park, Dock Walk, Chesterfield,
Derbyshire S40 2QR. Sales: 01246 200 222
Send large letter stamp for Catalogue

MISCELLANEOUS

VALVES AND ALLIED COMPONENTS? For free stock list and/or advice, please contact me: geoffdavies337@gmail.com Telephone: 01788 574774

PIC DEVELOPMENT KITS, DTMF kits and modules, CTCSS Encoder and Decoder/Display kits. Visit www.cstech.co.uk

Electrical Industries Charity (EIC)
We help people working in the electrical, electronics and energy community as well as their family members and retirees.
We use workplace programmes that give the industry access to financial grants and a comprehensive range of free and confidential services.
www.electricalcharity.org
electrical industries charity

COMPONENTS AS JOB LOT Large stock. Transistors, Diodes, Logic, Memory and Analogue parts. 1000s of passive items. Catalogued and sorted. 'New Old Stock' in racks. Email: rojobarn@gmail.com

COAST ELECTRONICS
BREAKOUTS-COMPONENTS-
CONTRACT DESIGN-3D PRINTER PARTS-
MUSICAL-MICROCONTROLLERS
WWW.COASTELECTRONICS.CO.UK

Andrew Kenny – Qualified Patent Agent
EPO UKIPO USPTO
Circuits Electric Machinery Mechatronics
Web: www.akennypatentm.com
Email: Enquiries@akennypatentm.com
Tel: 0789 606 9725

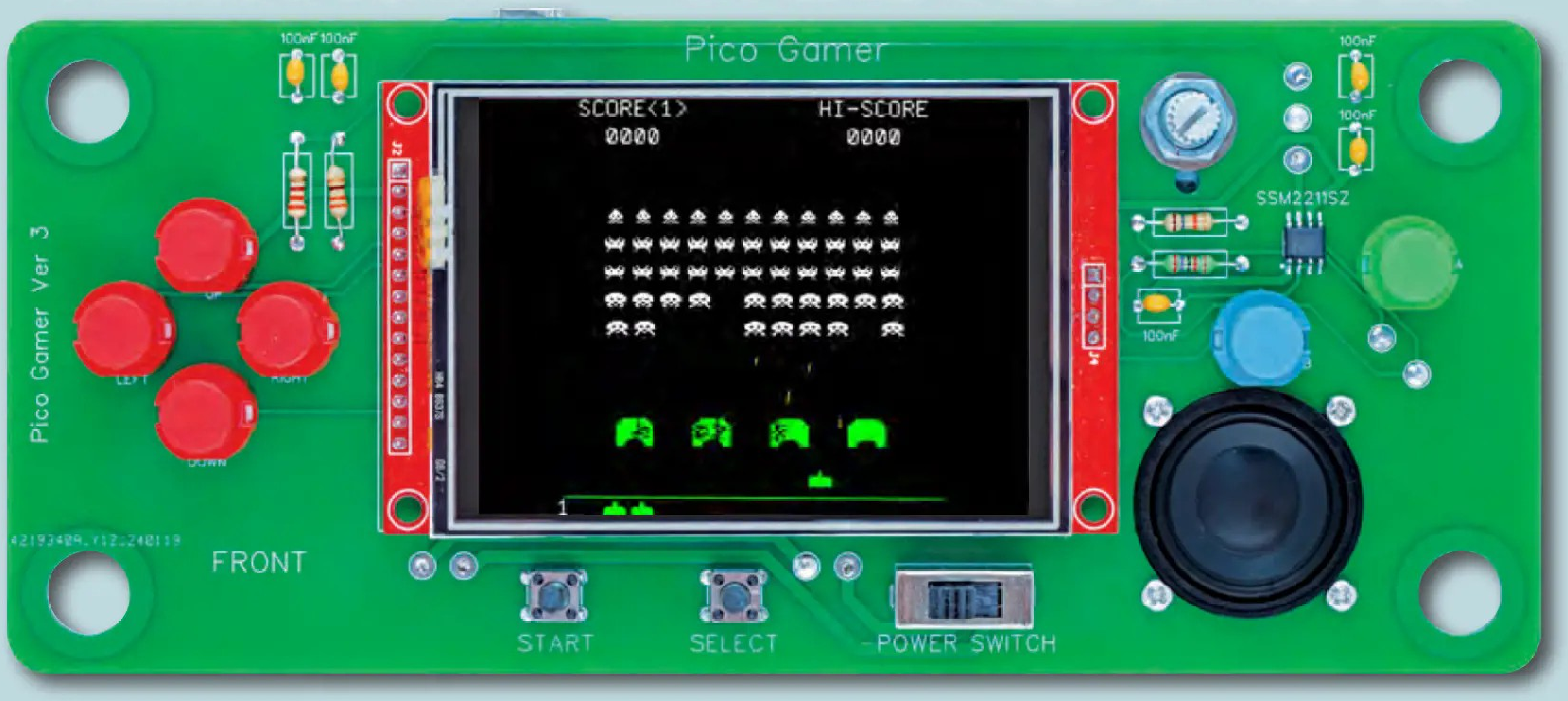
ADVERTISING INDEX

ENIGMA COMPONENTS SHOP 27
FLOWCODE .... Inner front cover
HAMMOND ELECTRONICS Ltd. 25
MICROCHIP TECHNOLOGY .... Outer back cover
PCBWAY 3
POLABS 46
SILICON CHIP MAGAZINE 47
STEWART OF READING 36

Advertising mailing address
Electron Publishing Australia
PO Box 194
Matraville NSW 2036
Australia
Email pe@pemag.au
Web www.electronpublishing.com

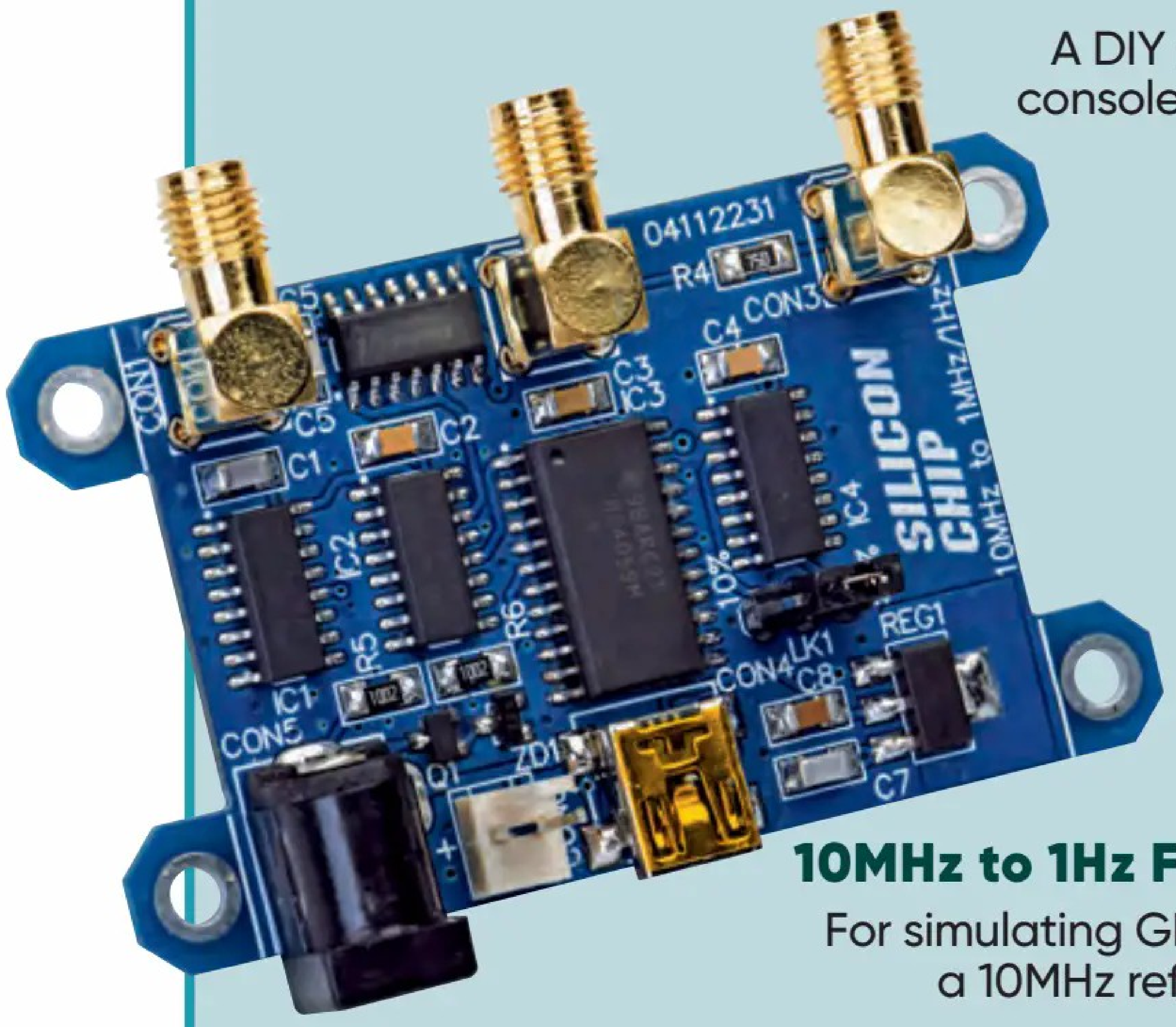
For editorial contact details, see page 2.

Next Month – in the March issue



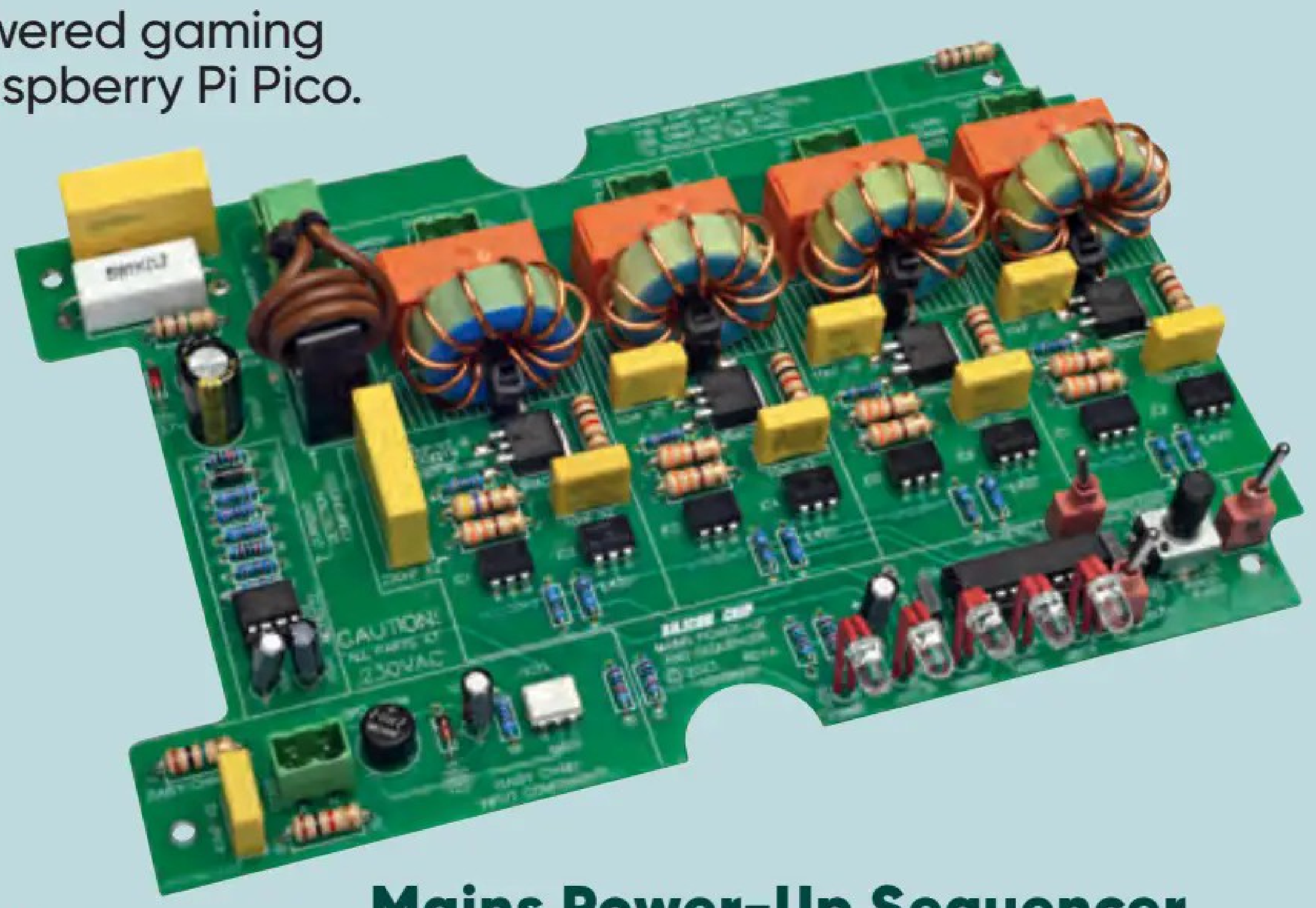
The Pico Gamer

A DIY retro battery-powered gaming console based on the Raspberry Pi Pico.



10MHz to 1Hz Frequency Divider

For simulating GPS 1PPS signals from a 10MHz reference source.



Mains Power-Up Sequencer

Part two: building it and setting it up.

On sale 5th of February, 2025

Content may be subject to change

Practical Electronics

Subscriptions hotline

To subscribe or renew online, paying by credit/debit card or PayPal, please visit our shop at: www.electronpublishing.com

For those wishing to pay by direct debit, cheque or over the telephone, please contact 'Select Publisher Services' by calling 01202 087631, or send a cheque (payable to: 'Practical Electronics') with your details to:

Practical Electronics Subscriptions, PO Box 6337, Bournemouth BH1 9EH, United Kingdom

Remember, we print the date of the last issue of your current subscription in a box on the address sheet that comes with your copy.

Digital subscribers, please call 01202 880299 or visit: www.electronpublishing.com

Published on approximately the first Thursday of each month by Silicon Chip Publications, U1 234 Harbord Road Brookvale NSW 2100 Australia. Printed in England by The Manson Group, Reynolds House, 8 Porters Wood, Valley Road Industrial Estate, St Albans AL3 6PZ. Distributed by Seymour, 86 Newman St, London W1T 3EX. Subscriptions UK: £33.99 (6mo); £59.99 (12mo.); £114.99 (2yrs). EUROPE: airmail service, £38.99 (6mo); £69.99 (12mo); £129.99 (2yrs). REST OF THE WORLD: airmail service, £46.99 (6mo); £84.99 (12mo); £164.99 (2yrs). Make payments to 'Practical Electronics', Practical Electronics Subscriptions, PO Box 6337, Bournemouth BH1 9EH United Kingdom. Email: pesubs@selectps.com. PRACTICAL ELECTRONICS is sold subject to the conditions that it shall not, without the written consent of the Publishers first having been given, be lent, resold, hired out or otherwise disposed of by way of Trade at more than the recommended selling price on the cover, and that it shall not be lent, resold, hired out or otherwise disposed of in a mutilated condition or in any unauthorised cover by way of Trade or affixed to or as part of any publication or advertising, literary or pictorial matter.

Did you know our online shop now sells the current issue of *PE* for £5.99 inc. p&p?

Practical Electronics
The UK's premier electronics, computing and maker magazine
Circuit Surgery
Implementing digital sinc low-pass filters
The History of Electronics
Part two covers inventors born between 1804 and 1847
Precision Electronics
Choosing and using highly accurate op amps
Switching mains-powered devices on and off in sequence
Transmitting sound using a laser beam
Model Railway Points Controller
PLUS!
Techno Talk – could an AI help to keep you company?
Cool Beans – using NeoPixels for a colour matrix display
Net Work – wireless weather stations and nuclear power
Feb 2025 £5.99
www.electronpublishing.com
@practicalelec
practicalelectronics
Precision Electronics
How to make precise and repeatable measurements
High-quailty microphone preamp for stage & studio work
Jan 2025 £5.99

You read that right! We now sell the current issue of your favourite electronics magazine for exactly the same price as in the High Street, but we deliver it straight to your door – and for UK addresses we pay the postage. No need to journey into town to queue outside the newsagent. Just go to our website, set up an account in 30 seconds, order your magazine and we'll do the rest.

www.electronpublishing.com

IGBT 7: Power, Performance and Precision

Superior Power Density With Versatility and Efficiency

Discover the power of versatility with IGBT 7 modules, designed to deliver unmatched flexibility, efficiency and reliability across multiple power applications. Whether you need solutions for wind, solar, railways, aviation or data centers, IGBT 7 high-performance modules provide a balance of ease of use, power density and cost efficiency.

Key Features

- **Multiple applications:** General-purpose drives, wind, solar, railways, CAV, MEA, data centers and more
- **Innovative packaging:** 62 mm D3/D4 and SP6C, SP1F, SP6LI options
- **Flexible topology support:** 1200V to 1700V, 50A to 900A, three-level NPC, full-bridge, T-type and more
- **Superior performance:** Lower power losses, higher power density and enhanced reliability

Unlock the full potential of your power systems with IGBT 7 modules. Featuring advanced technology, innovative packaging and broad topology support, IGBT 7 modules are engineered to reduce power losses, increase system efficiency and provide the reliability you need.
Elevate your energy solutions today with IGBT 7 modules.

microchip.com/IGBT7

The Microchip name and logo and the Microchip logo
are registered trademarks of Microchip Technology
Incorporated in the U.S.A. and other countries. All other
trademarks are the property of their registered owners.
© 2024 Microchip Technology Inc. All rights reserved.
MEC2595A-UK-12-24